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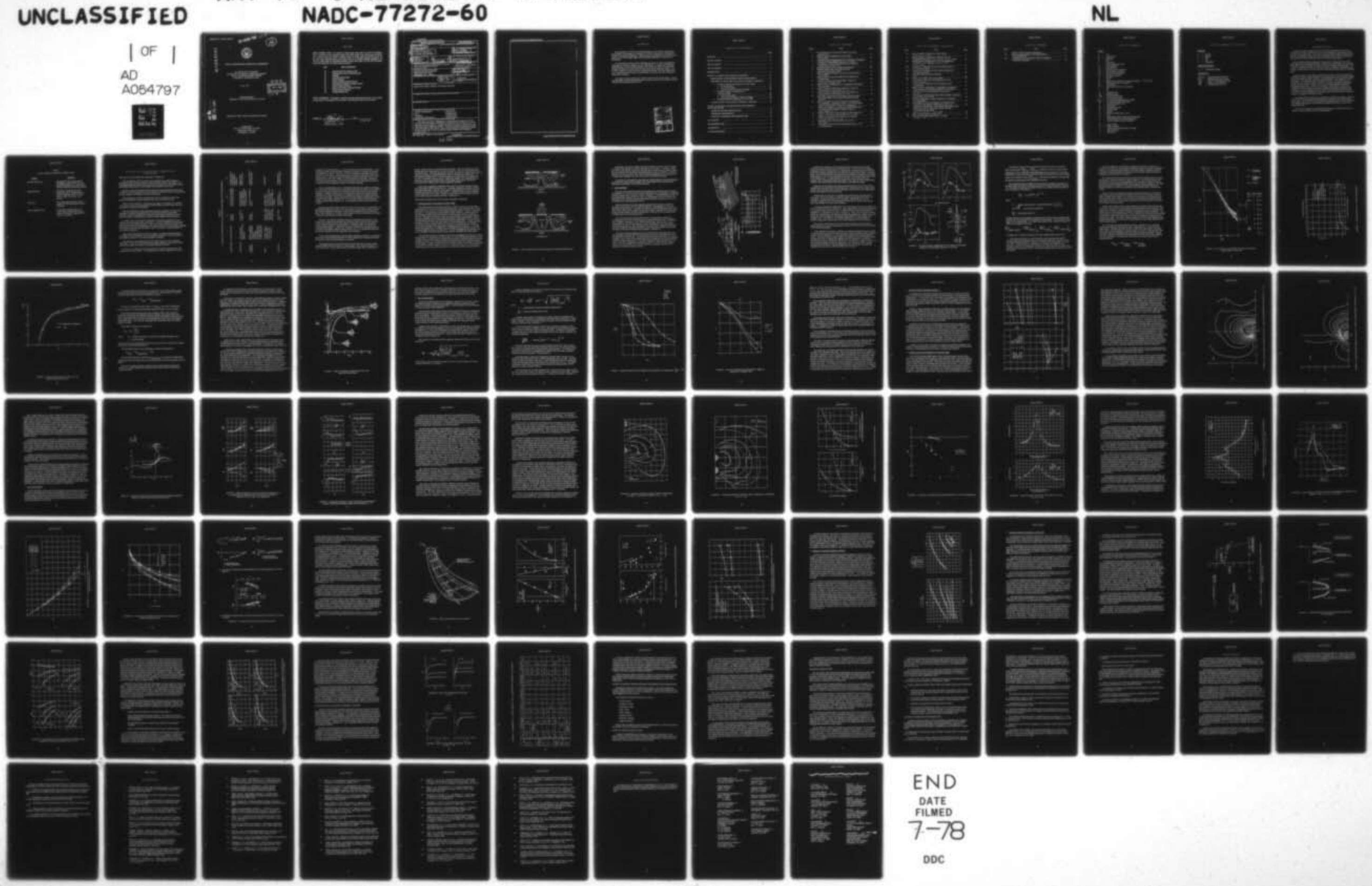

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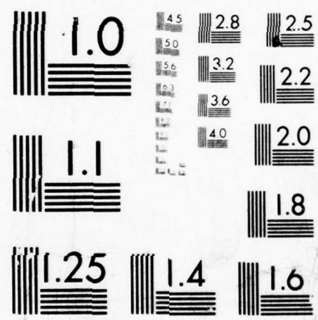

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V/STOL AERODYNAMICS TECHNOLOGY ASSESSMENT

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The objective of this investigation is to determine the status of V/STOL aerodynamics technology; evaluating the capabilities and limitations of various techniques and the validity of methods through correlations of predictions with wind tunnel and/or flight test results. This interim report presents the results of the first phase of this effort; a survey and assessment of published methods and test results and a survey of industry applied methods and technology problem areas.

393 532

SUMMARY

Recent interest in V/STOL aircraft applications to Navy mission requirements has prompted an investigation of the status of V/STOL aerodynamics technology and adequacy of prediction techniques. Reliable prediction techniques are required for all phases of the V/STOL flight regime and all concepts applicable to future Navy requirements.

It is the objective of this study to determine the status of V/STOL aerodynamics technology for concepts suitable for Navy application, to evaluate the capabilities and limitations of each developed method, and to assess the validity of the methods through correlations of predictions with wind tunnel and/or flight test results. The V/STOL concepts for which applicable aerodynamic methods have been considered to date are the lift plus lift/cruise, vectored-thrust, tilt cruise, and thrust augmented wing V/STOL aircraft.

This interim report presents the results of the first phase of this effort; a survey and assessment of published methods and test results, and a survey of industry applied methods and technology problem areas.

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LIST OF SYMBOLS

Symbols

A	-	Area
AR	-	Aspect Ratio
b	-	wing span
B	-	body
c	-	wing chord
$\bar{c}$	-	mean aerodynamic chord
C_D	-	drag coefficient
C_L	-	lift coefficient
C_m	-	pitching moment coefficient
C_μ	-	jet momentum coefficient
C_N	-	normal force coefficient
C_P	-	pressure coefficient
d	-	diameter
D	-	drag
$\bar{D}$	-	angular mean diameter of wing/body planform $\frac{1}{\pi} \int_0^{2\pi} r \, d\theta$
D_e	-	equivalent diameter of single jet
F_N	-	normal force
H	-	height above ground of jet exit plane
J	-	jet
L	-	lift
$\dot{M}$	-	momentum flux
M_y	-	pitching moment
NPR	-	nozzle pressure ratio
P	-	sum of jet perimeters
$P_{T_{sp}}-P$	-	total pressure differential at jet efflux
q_x	-	jet centerline dynamic pressure
S	-	wing/body planform area
S_j	-	jet exit area
S_p	-	wing planform area
T	-	total jet thrust
U	-	velocity
V_e	-	effective velocity ratio, U_∞/U_j
W	-	wing
X	-	longitudinal distance along aircraft centerline
Y	-	lateral distance from aircraft centerline
Z	-	vertical distance along jet centerline
α	-	angle of attack
β	-	angle of sideslip
γ	-	vortex filament strength per unit length
δ	-	deflection angle
Λ	-	wing sweep

LIST OF SYMBOLS (Continued)

Subscripts

e	-	jet exit
f	-	fountain
F	-	flap
j	-	jet
∞	-	freestream

Mathematical Symbol

$\Delta(\ )$	-	incremental quantity

Abbreviations

GD/CON	-	General Dynamics/Convair
MAC	-	McDonnell Aircraft Company
NADC	-	Naval Air Development Center
ONR	-	Office of Naval Research
VSD	-	Vought Systems Division

INTRODUCTION

Recent Navy plans to emphasize V/STOL aircraft applications require the development of accurate methods to predict aircraft aerodynamic characteristics in the critical V/STOL flight mode. The various existing methods and body of test data have been developed generally without overall coordination, and to a large extent address only specific V/STOL concepts and areas of the V/STOL flight regime.

Since reliable prediction techniques are required for all phases of the V/STOL flight regime and all concepts applicable to future Navy requirements, it is necessary to assess the present capability to predict V/STOL aerodynamic characteristics. The results can expose those areas for which the prediction capability is deficient or nonexistent. Future effort can then be directed to eliminate the deficiencies or technology gaps.

It is the objective of this study to determine the status of V/STOL aerodynamics technology for those concepts suitable for Navy applications and to evaluate the validity of analysis methods through correlation of predictions with wind tunnel and/or flight test results. The approach involves two phases of effort. The first phase, presented herein as an interim report, includes a survey and assessment of published methods and test results, together with a survey of industry applied methods and technology problem areas. This survey included a comprehensive review of the available V/STOL aerodynamics prediction methods assessing the capabilities and limitations of various methods with areas of application and deficiencies described. A summary of these technology survey results, conclusions and research recommendations is presented in this interim report.

The second phase will involve the correlation of predicted aerodynamic characteristics with test data using the methods found most promising from this first phase assessment. This work will be accomplished in conjunction with a V/STOL DATCOM type development program incorporating the appropriate methods in the DATCOM development work.

The V/STOL concepts for which applicable aerodynamic methods have been considered to date are summarized in the following table.

TABLE I

V/STOL VEHICLE CONCEPTS CLASSIFICATION

Concept	Definition
Lift Plus Lift/Cruise	Combination of one or more direct lift engines or fans with two or more lift/cruise engines; e.g., NASA/Navy lift fan research and technology aircraft.
Vectored-Thrust	Lift/cruise configurations which directs fan air or exhaust gases to nozzles containing vanes or deflectors to vector the thrust; e.g., Harrier.
Tilt Cruise	Lift/cruise engine/nacelle arrangements which tilt the nacelles for thrust deflection.
Thrust Augmented Wing	Cruise engine arrangements with exhaust flow diverters which supply ejectors distributed in segments of the wing; e.g., XFV-12.

REVIEW OF AERODYNAMIC PREDICTION METHODS

AERODYNAMIC COMPUTERIZED MODELING TECHNIQUES

In the development of new aircraft of unconventional type, model testing has played the decisive role in all aspects of the aerodynamic analysis and design. It is increasingly apparent, however, that computerized techniques of aerodynamic analysis and prediction may assume a wider usage in the immediate or near future.

Recently, numerical computation procedures have been assessed by NASA Ames, reference 1, for its potential as a tool for complete aerodynamic analysis and prediction, perhaps eventually in substitution of wind tunnel testing.

The development of V/STOL aircraft seems to be an example for which computerized aerodynamic analysis techniques may play a more decisive role.

Table II, from reference 1, summarizes the stages of development of computerized solutions of the governing equations of fluid mechanics and their status for use in aerodynamic computer flow simulation.

With the development of large high-speed electronic computers, not only is the application of analytical techniques such as the lifting surface theories greatly expedited, but the development and execution of more advanced techniques, such as the panel methods, finite-difference and finite element methods become possible.

A recent review of the analytical techniques to calculate aerodynamics of conventional aircraft has been given in reference 2. The use of potential flow theories is noted in nearly all of these techniques. This is due to the fact that the solution of the potential flow equations has been found to give good results for lift and moments, although not as good accuracy in drag calculations, and is much easier to obtain compared to Navier-Stokes equations.

Many of these lifting surfaces theories, based on a small perturbation analysis with respect to the free stream, such as Woodward, reference 3, have been shown to be adequate for many CTOL aircraft aerodynamic problems.

These theories can be applied directly to V/STOL aircraft in the conventional flight mode. This is valid even under powered flight conditions, since the flow fields involved can usually be treated by a linearized potential flow theory.

However, for V/STOL aircraft in the hovering or even the transition mode, the situation can be quite different. Two phenomena are uniquely significant for V/STOL

TABLE II

STAGES OF APPROXIMATION TO GOVERNING EQUATIONS OF FLUID MECHANICS

	I	II	III	IV
Characteristics	Inviscid linearized	Inviscid nonlinear.	Viscous, time-averaged Navier-Stokes equations.	Complete viscous, time-dependent Navier-Stokes equations.
Approximation	Viscous and non-linear inviscid terms neglected.	Viscous terms neglected.	No terms neglected; turbulent momentum, energy, and heat-transport terms modeled.	Subgrid-scale motion modeled.
Principal Limitations	Slender configurations; small angle of attack; perfect gas; no transonic flow; no hypersonic flow; no flow separation.	No flow separation.	Accuracy of turbulence model.	Accuracy of Navier-Stokes equations.
Status	2D flows, 1930s; 3D flows, 1960s; used in current aircraft design.	2D flows, 1971; 3D flows, 1975; early stages of application to aircraft design.	2D flows 1975; 3D flows, 1978 ? Early stage of development with simple turbulence models for 2D flows.	Mid-1980s ?
Pacing item	—	Code development.	Development of improved turbulence models.	Development of advanced computer.

aircraft in the hovering mode, i.e., the jet induction and the ground effects. In conventional aircraft, the ground effect on lift can be treated by a potential flow theory in a satisfactory manner. However, in V/STOL flight the jet induction and ground effects are a much more complex phenomenon involving the interaction of the jet with the free stream, with the aircraft, and with the ground in which fluid viscosity and turbulence play a key role. Indeed, in a recent solution by Kotansky, reference 4, for hovering in ground effect, viscosity and turbulence of the flow exterior to the jet is included with the resulting flow shown to be highly rotational.

From a heuristic point of view, computerized analysis and prediction techniques for V/STOL aircraft performance, particularly in the hovering mode, must eventually take into account the viscosity and turbulence effects inherent in the Navier-Stokes equations. Recently, efforts have been initiated to develop analysis and prediction techniques for V/STOL aerodynamics by taking into account the viscosity and turbulence of the flow field. Various approaches have been adopted including the use of the complete Navier-Stokes equations, the use of "parabolic Navier-Stokes equations" and the viscous-inviscid analysis, etc. An operational technique is however not yet in sight.

Existing operational methods which have been devised by several investigators, use potential flow theories to account for jet induction by a distribution of sinks, sources and doublets coupled with paneling or vortex lattice techniques for the aircraft surfaces. Such methods are, of course, semi-empirical because experiments are needed to supply the necessary jet induction information.

However, even with the limitations inherent in potential flow solutions, the development of computerized potential flow techniques which model the jets based on a body of experimental data are approaching a reasonable status for prediction of major induced aerodynamic characteristics of V/STOL aircraft, at least for the transition flight regime. A discussion of present empirically based approaches used to model the jet induction effects, such as Wooler, et. al., is presented in Section 2 along with a discussion of their capabilities and limitations.

All the current potential flow aircraft surface modeling techniques are essentially based on the same theoretical grounds, but basic differences in accuracy arise from the manner in which aircraft surfaces are modeled.

The Douglas Neumann method developed by Smith and Hess is a panel method employing distributions of both sources and doublets. This computer program employs flat panels to model lifting bodies of arbitrary shape with no restriction on

the free stream velocity or small perturbation applied. However, difficulties in flow leakage and large computing time (or lack of accuracy) in the numerical solution have been encountered. Under the sponsorship of NADC, reference 5, a higher-order surface singularity technique is being developed by Hess to overcome these difficulties. In this technique, singularities of varying strength and second-order curved panels will be used. In addition, incorporation of a "geometric package" for implementing computer input data, being developed under NASA/Langley sponsorship, will also be carried out for the higher-order surface singularity technique.

Other surface singularity techniques such as the vortex lattice method, Douglas EVD (Equivalent Vortex Distribution), etc., although essentially equivalent in solving the same potential flow equations, differ mainly in the application of surface boundary conditions and methods of numerical analysis. A problem being actively investigated at the present time is the proper "mixing" of source and vortex (or doublet) distributions in optimizing the computing efficiency, (reference 6).

DISCUSSION OF DEVELOPED ANALYTICAL/EMPIRICAL METHODS

1. Propulsion Induced Aerodynamics in Hover Flight

The induced forces and moments acting on a V/STOL aircraft in hovering flight result from one or both of two viscous flow phenomenon: jet entrainment and a fountain flow formed by two or more jets interacting at the ground plane. These are illustrated in figure 1. Jet entrainment causes otherwise static ambient air to flow toward the jets resulting in locally reduced pressures on airframe under surfaces producing a lift loss. The effect occurs both in and out of ground effect, but is greatly amplified in ground proximity due to the increased entrainment of the ground wall jets, and the reduced volume between the aircraft surfaces and the ground plane. The pure entrainment effect (with no cross wind) can induce a lift loss amounting to 1 to 4 percent of the jet thrust out of ground effect (OGE) and as much as 10 to 20 percent of jet thrust at typical take-off heights (IGE) depending on configurational and jet factors. Principal factors affecting lift loss, in addition to jet exit height above the ground, are the ratio of vehicle planform area to jet efflux area, jet nozzle arrangement, wing position relative to jet efflux, crosswind velocity and jet "quality" (turbulence level and profile).

The formation of jet-flow "fountains" requires an impingement surface and is, therefore, peculiar to operation close to the ground. It is also configuration dependent in that multiple jets are required with the fountain induced upload on aircraft surfaces depending strongly on relative jet to surface location, jet number and spacing, impingement angle and momentum "capture" potential of the vehicle under surface. By judicious arrangement of jets and/or momentum capture devices (e.g., bombracks, doors, etc.), the fountain induced upload can in some cases be made to override the entrainment suckdown effect.

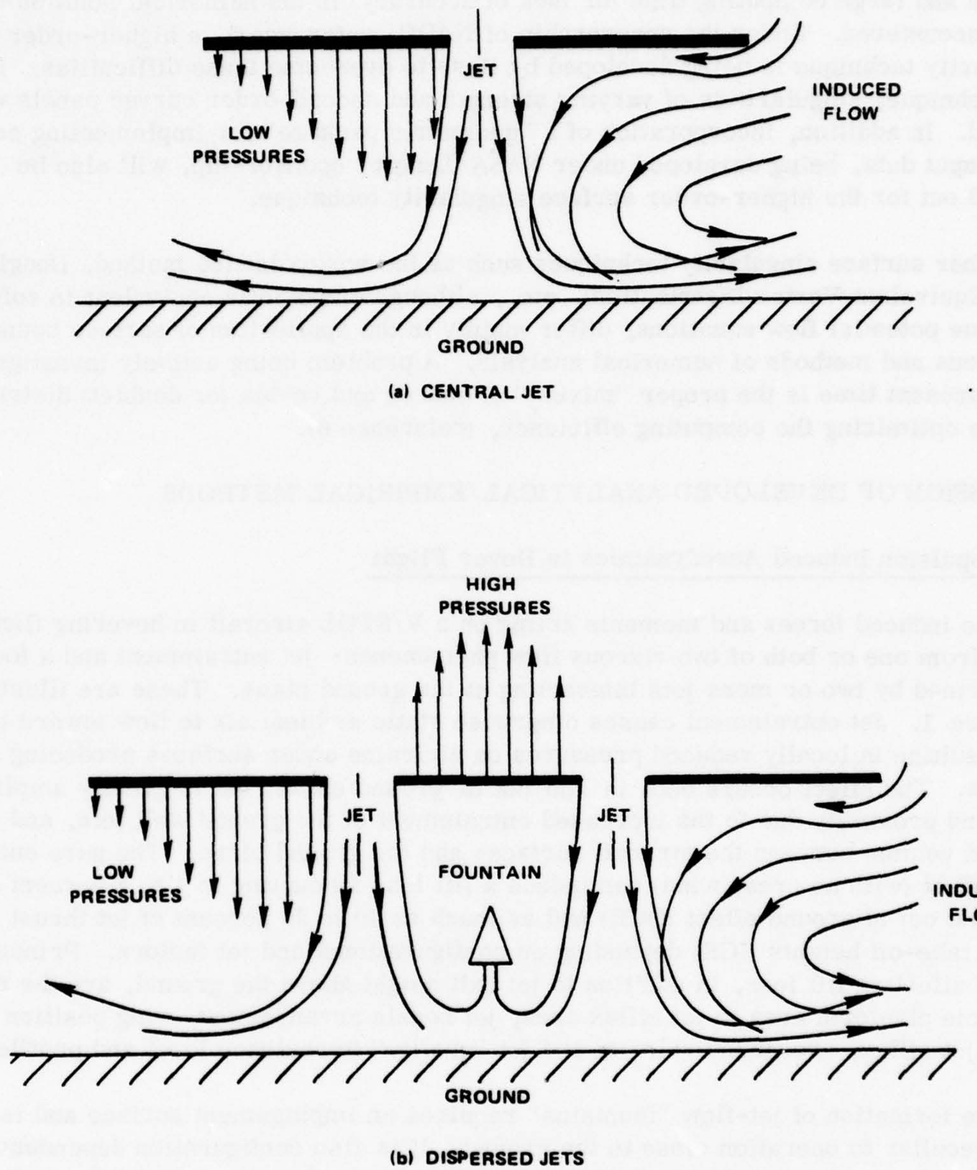


FIGURE 1 - Flow Patterns Near Ground with Central Jet and with Dispersed Jets

Additionally, the fountain induced forces and moments that occur with the vehicle in a pitch or roll attitude is a further important area of concern. Typically, a multi-jet V/STOL with laterally spaced jets near the wing will experience an unstable rolling moment variation with roll attitude in ground proximity due to two effects: increased lift loss on the low wing side, and a shift of fountain impingement to the high wing side. A similar pitch instability may also occur due to fore and aft jet spacing.

A discussion of representative analytical and experimentally derived methodologies to predict these induced effects together with a description of their limitations and deficiencies is presented in the following sections.

a. In Ground Effect

The most recent published analytical methodology for predicting multi-jet induced aerodynamics of V/STOL aircraft hovering in ground effect was developed by McDonnell Aircraft Company under contract to NADC, reference 7. The methodology basically employs high quality empirical data as a basis for modeling the free jets, wall jets and fountain flows and calculates the induced interference effects on the aircraft by use of a modified Hess aircraft panelling routine.

Figure 2 illustrates the source panelling approach that was used to model the aircraft surfaces and the free and wall jet boundaries corresponding to the viscous entrainment regions shown. Potential flow solutions for the entrainment induced suckdown forces and moments employ the standard boundary condition of no normal flow on the aircraft surfaces, and the predefined inflow velocities on the jet panels based on empirically derived entrainment data.

Free jet entrainment is based upon the data of Kleis and Foss, reference 8, recognizing that some data spread occurred in tests conducted by other investigators (e.g. Wyganski, reference 9, and Trentacoste and Sforza, reference 10). Free jet development and self similar properties of fully developed jets were also defined from these data sources. Flow characteristics of the wall jet, including entrainment rate and azimuthal momentum distribution, which account for inclined jet conditions are based on the data of Donaldson and Snedecker, reference 11.

Formation of ground stagnation lines are calculated from knowledge of the wall jet momentum and the flow interactions between two or more wall jets giving rise to the fountain flow distributions. The fountain flow effects are determined in a separate computer routine based on the computed ground flow stagnation lines and the resulting vertically rising momentum flux. The total "available" fountain momentum flux for the 2, 3 and 4 jet arrangements illustrated in figure 2C is converted into impingement forces and moments on the aircraft surfaces as a function of surface area exposed, and dynamic pressure recovery.

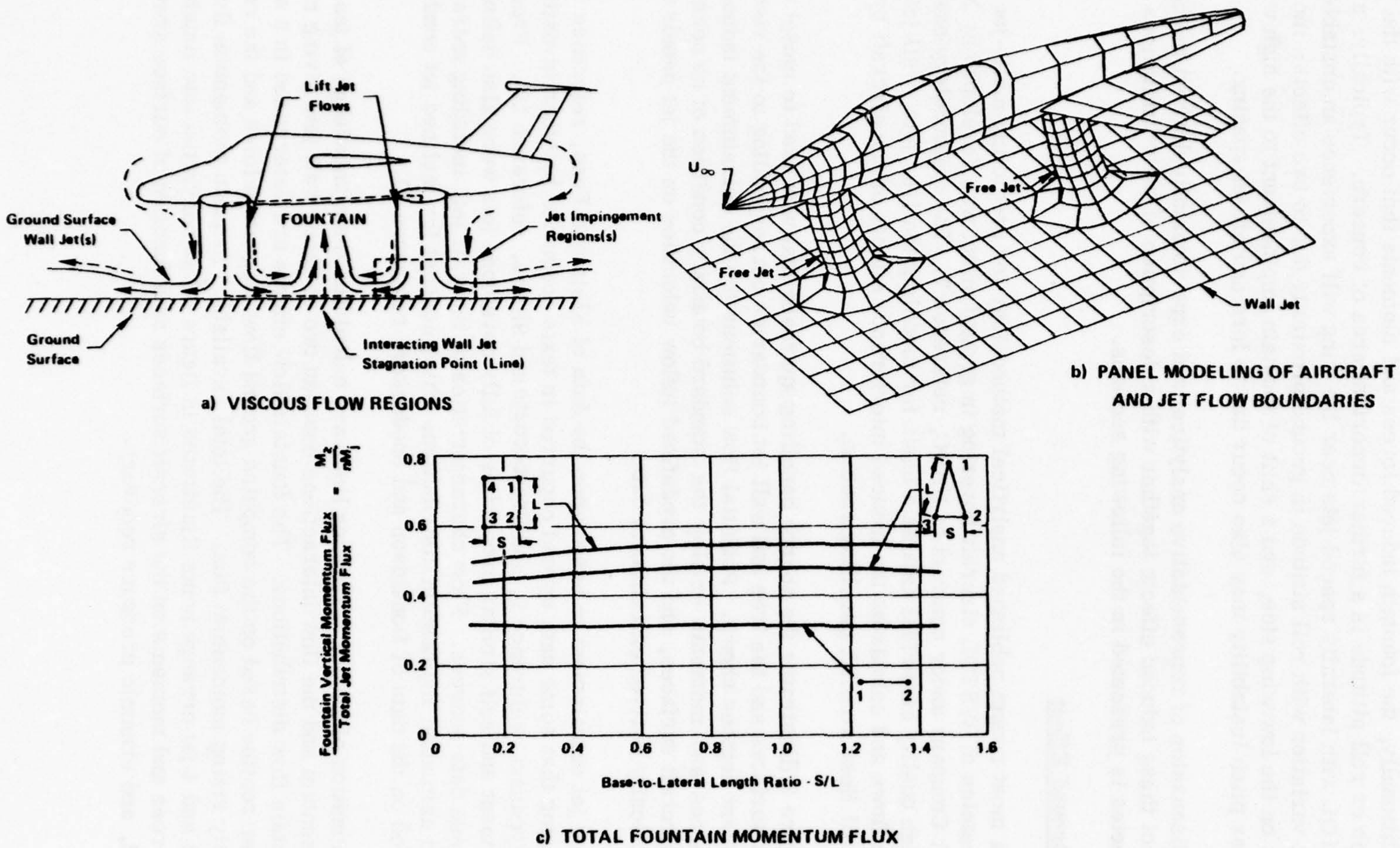


FIGURE 2 - Multi-Jet Induced Aerodynamics Hover Flight - IGE & OGE

Fountain flow model tests were conducted during the program to help define fountain self similar profiles and jet spreading rates. As part of that test program, impingement forces were measured on a representative aircraft model and were compared with predicted impingement forces based on the fountain flow model. Measured forces were substantially lower than predicted and actually went negative at low model heights (figure 3). This result suggested the presence of additional entrainment caused by the fountain itself. An approximation for this effect was incorporated in the computer code by assuming fountain entrainment to be similar to free jet entrainment, creating a sink induced effect within the confines of the inner flow region.

Using the overall program, the predicted induced forces on the AV-8A V/STOL configuration were compared with model test data. Predictions of the suckdown effect seemed in line with test results, but the predicted fountain upload was substantially greater than measured in the model tests.

Further tests are required to investigate these fountain flow characteristics in more detail and to formulate an improved fountain and impingement model. Investigation of fountain formations and momentum distributions for cases of assymetric ground jet flows are also needed to better define a model of the induced forces and moments for the pitch/roll condition.

A similar computerized methodology to the MAC program for hover jet induced effects is reported by Siclari, reference 12. This method also uses the Hess panel routine for modeling aircraft surfaces but uses a slightly different form for paneling the jet boundaries, as discussed more fully in Section 2. Hover and low speed suckdown effects are computed based on empirical entrainment formulations, however the formulations that were developed for the fountain induced effects are not included in the computer code. The program is principally applicable to low speed transition. Limited comparisions with test data in low speed transition are given in Section 2.

Data sources and development of empirical formulations of hover jet induced effects applicable to various arrangements of multi-jet V/STOL aircraft are discussed in the following paragraphs.

Tests conducted by Margason, reference 13, determined induced lift and moments in ground effect for models with single and closely spaced multiple circular jets having various ratios of planform area to jet exhaust area and various jet nozzle pressure ratios. Evidence of positive fountain effects was apparent even for the closely spaced multiple jets (4 and 8) although the magnitude was not sufficient to overcome the induced lift loss due to entrainment. Similar data was obtained by Vogler, reference 14, for single and multiple circular and slotted jets. The circular jet data is in good agreement with Margason's results although the data point spread is so large that fountain effects are not as easily discernible from the data.

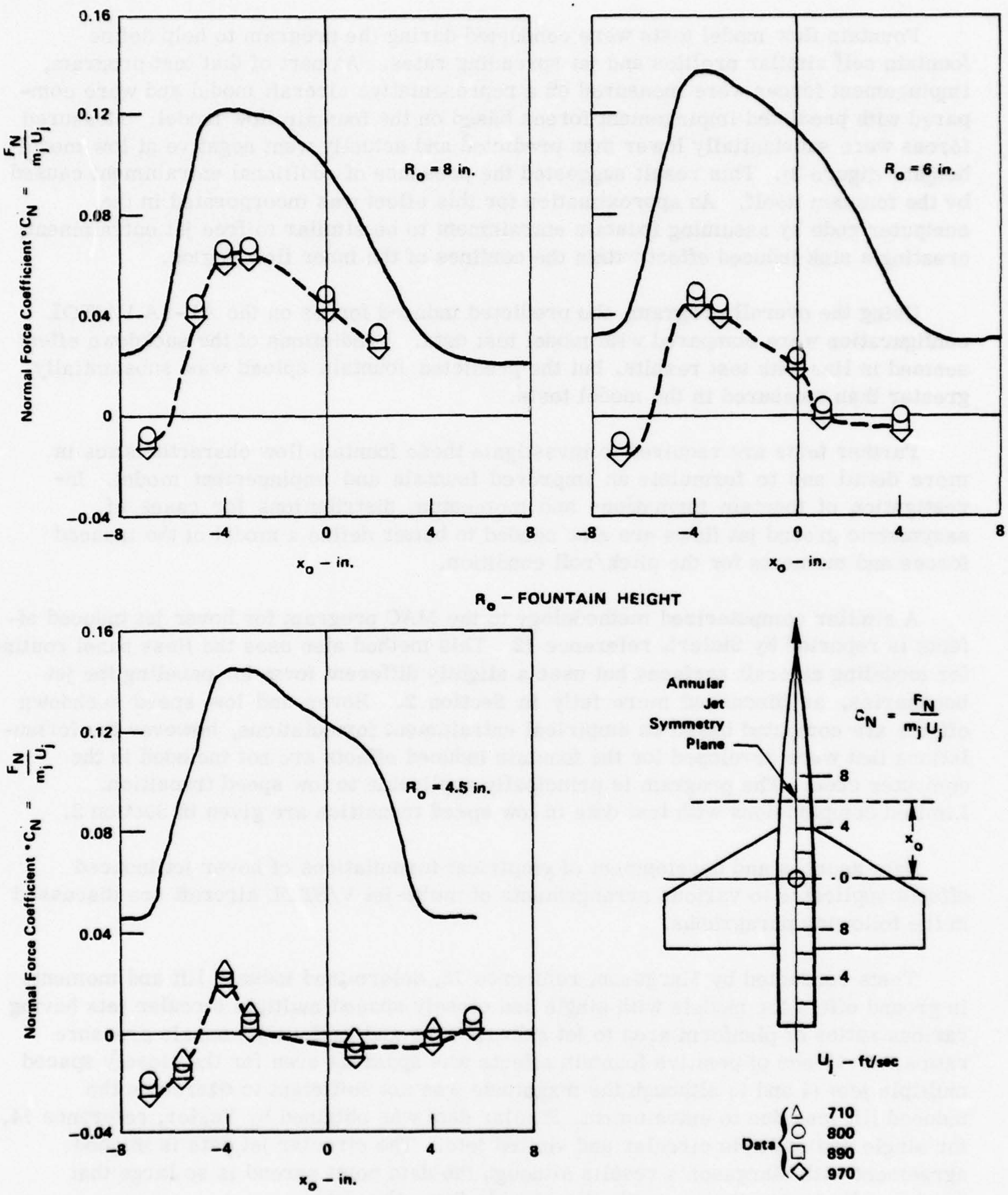


FIGURE 3 – Calculated Fountain Impingement Force Compared to Simulated Fountain Test Using Single Annular Jet, Low Wing

A preliminary check of the data indicates that the lift loss due to jet entrainment in ground effect $\left(\frac{\Delta L}{T}\right)_{IGE} - \left(\frac{\Delta L}{T}\right)_{OGE}$ is nearly the same for closely spaced multiple jets as for a single jet having equal planform to jet area ratio. It may thus be possible to extract from these and similar data in the literature, the direct fountain effects, and correlate results, $\left(\frac{\Delta L}{T}\right)_{FOUNT}$ with pertinent parameters including $\frac{H}{de}$, jet number and spacing and ratio of planform to jet area.

Pure entrainment lift loss effects may be similarly correlated for multiple jets using the format for lift loss correlations shown by Louisse and Marshall, reference 15. From their correlations for single circular jets, a useful empirical equation for pure jet suckdown is developed as:

$$\frac{\Delta L}{L_\infty} = 0.025 \left[H/\bar{D} - d_e\right]^{-1.70}$$

where:

$\bar{D}$ = angular mean diameter of wing/body planform $\left[\frac{1}{\pi}\int_0^{2\pi} r\,d\theta\right]$

$\bar{D} \approx 2\sqrt{\frac{S_p}{\pi}}$ (for jets under wing/body)

$\frac{\Delta L}{L_\infty}$ = Normalized thrust loss

The data used for this correlation was obtained from several sources including Wyatt, reference 16, who developed the original form of the equation. This equation is applicable to a low wing airplane. For a high wing airplane having a rounded fuselage, the method can be applied by pieces as:

$$\left.\frac{\Delta L}{L_\infty}\right|_{WING + BODY} = K\left.\left(\frac{\Delta L}{L_\infty}\right)_{BODY}\right|_{H_1} + \left.\left(\frac{\Delta L}{L_\infty}\right)_{WING}\right|_{H_2} - \left.\left(\frac{\Delta L}{L_\infty}\right)_{OVERLAP}\right|_{H_2}$$

A K factor of 0.7 is used to account for the round fuselage based on their data.

A preliminary analysis was made during this report preparation to further develop a generalized method for direct jet entrainment effects for multiple circular jet V/STOL aircraft in hover as a function of jet exit height and planform to jet exit area ratio. It was found that by extracting pure suckdown data (IGE) from the Margason, reference 13, and Volger, reference 14, single and multi-jet model tests, generally good comparisons with the Louisse and Marshall single-jet suckdown method were shown.

From this added data, a modification is suggested in the form of a decrease in slope at the low $H/(\overline{D}-D_e)$ values of the Louisse and Marshall correlation as presented in figure 4. By using calculated $H/(\overline{D}-D_e)$'s with this method, reasonable suckdown comparisons were found against test data from the Navy/NASA lift fan research and technology aircraft and the AV-8A Harrier.

The comparison between the Harrier test data and this modified Wyatt (or Louisse and Marshall) suckdown prediction is shown in figure 5. The test data has the characteristic rise in $\Delta L/T$ due to the appearance of the fountain at values of H/d_e less than about 5 whereas the modified Wyatt method only accounts for suckdown. The other data points shown are obtained from the MAC prediction program (suckdown and fountain) showing the excessive overprediction of the fountain effect, discussed previously.

Figure 6 shows a comparison between the measured suckdown on a model of the NASA lift fan research demonstrator (tested in the Ames 40 x 80 facility) compared with the modified Wyatt method. The measured total suckdown was obtained by operating each of the three engines one at a time and measuring engine gross thrust and main balance lift force. With all engines operating, the main balance force contained both suckdown and fountain force.

Further data analysis will be needed to confirm the empirical multi-jet suckdown correlation, and to further develop empirically derived fountain induced effects. This appears to be possible in establishing major induced effects in hover; using data from further tests involving systematic variations in configuration and jet parameters. Two such programs are presently underway. One is sponsored by ONR to GD/CON involving model tests to single and multiple jets with various jet locations, spacings and jet to planform area ratios. The other program sponsored by NADC will investigate dynamic ground plane effects on an array of jet model designs from which static effects are obtained as baseline data.

In a recent test and analysis effort by Karemaa, reference 18, an empirical method was developed for the fountain effect, using data from a variety of jet/flat plate models. The basic approach used was to first test a single nozzle jet issuing from a plate in close proximity to a mirror image of the plate. From the force measurements, the direct entrainment lift loss of the one jet was determined. Forces were then measured with the two plates connected and with two jet nozzles operating (one from each plate). The difference between the two measurements is the net fountain effect as:

$$\Delta L_{f_{NET}} = (\Delta L)_{\substack{\text{2 plates} \\ \text{2 nozzles}}} - 2\,(\Delta L)_{\substack{\text{one plate} \\ \text{one nozzle}}}$$

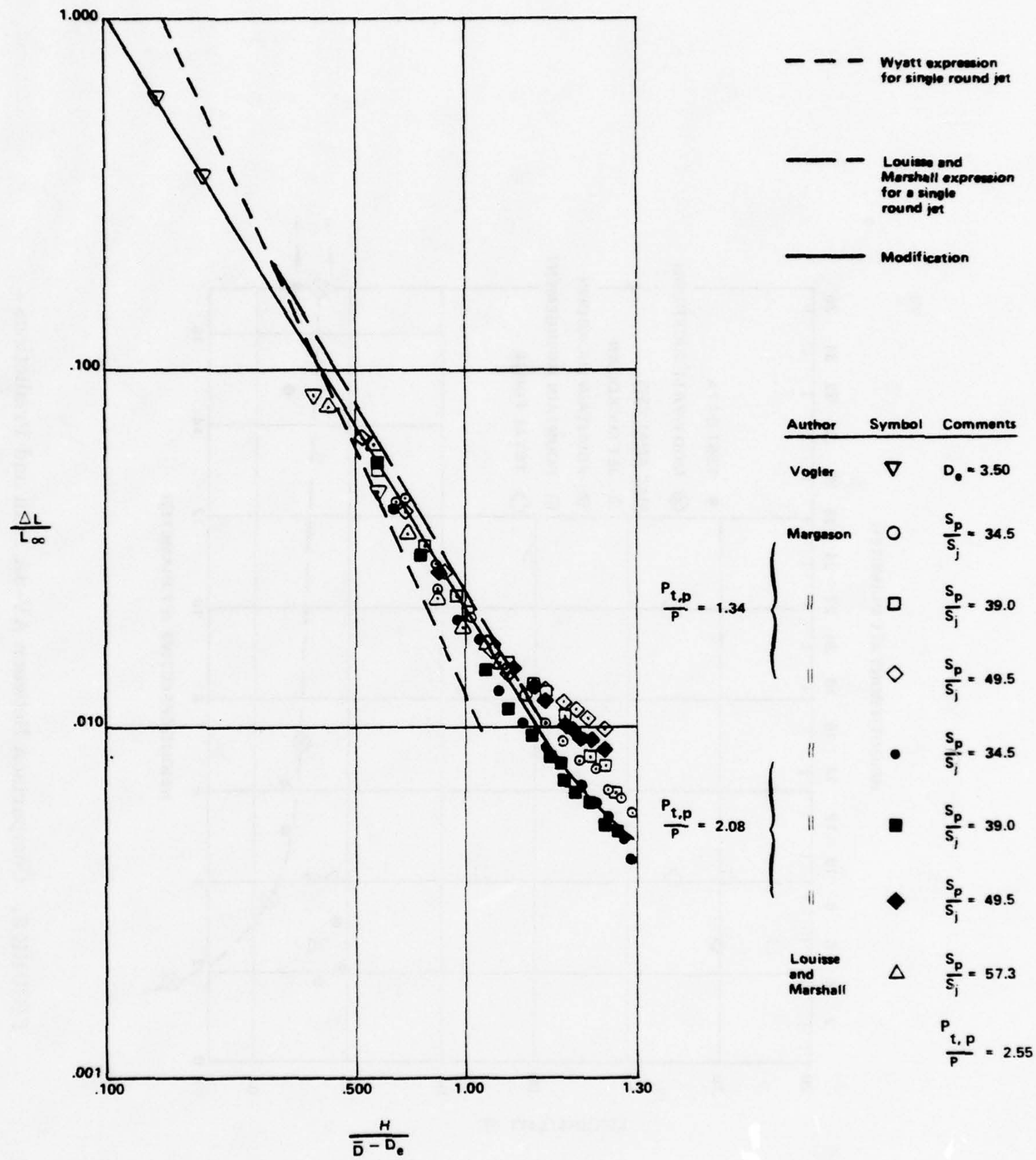


FIGURE 4 - Jet Suckdown in Ground Plane Proximity for Single and Closely Spaced Circular Jets

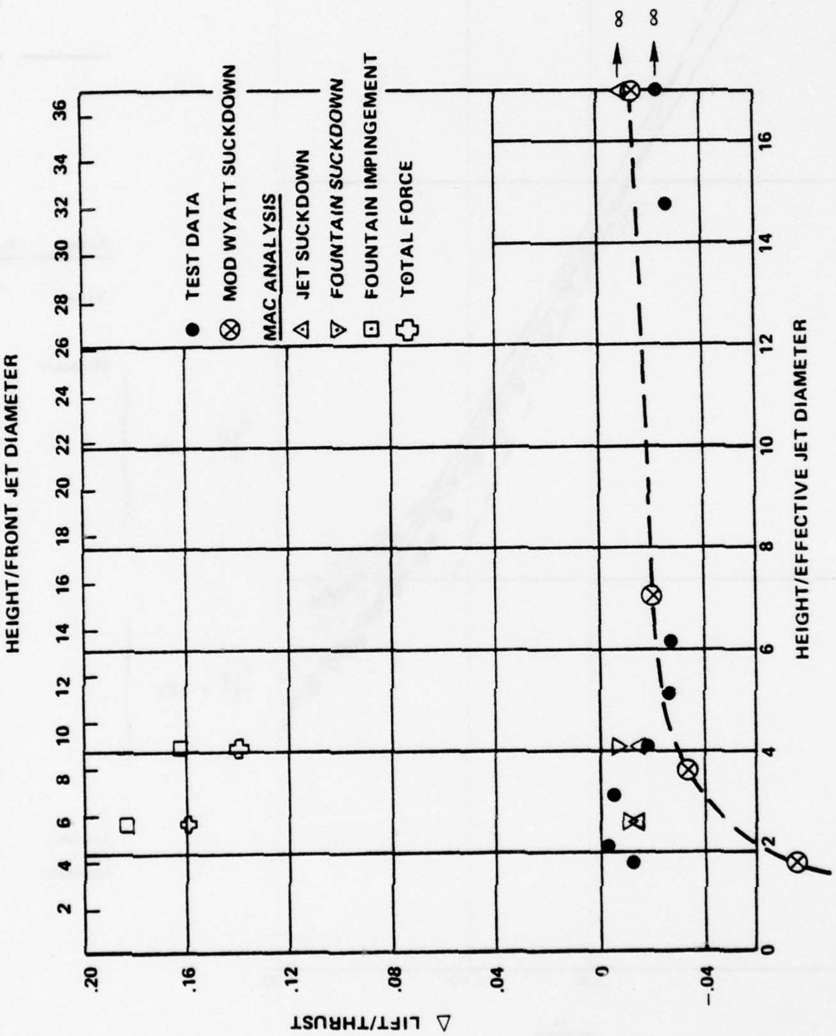


FIGURE 5. Comparison Between AV-8A Data and Predictions

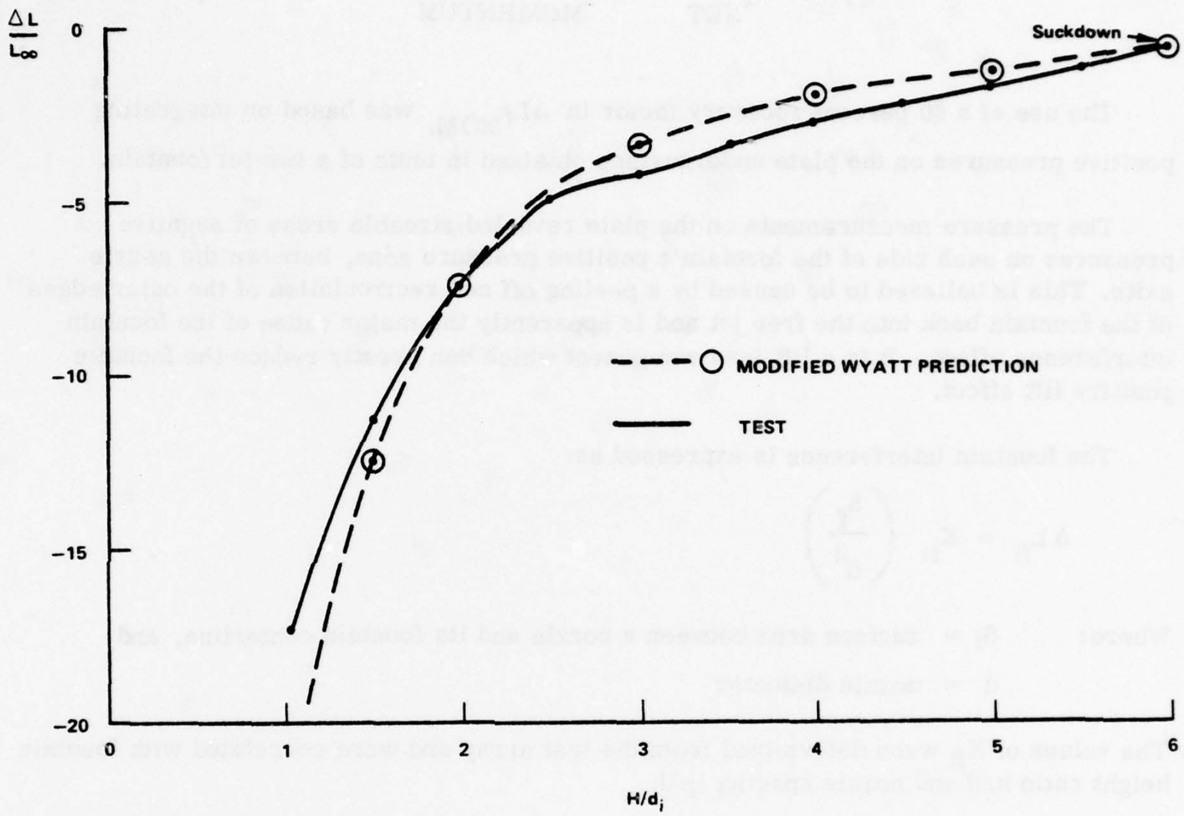


FIGURE 6 - Suckdown Induced Lift on the NASA Lift Fan Research Demonstrator Model

A calculated fountain force based on a 60 percent recovery of the fountain momentum flux is then subtracted from this net fountain force. The difference is a lift loss increment attributable to a fountain interference, given as:

$$\Delta L_{fi} = \Delta L_{f_{NET}} - \Delta L_{f_{MOMENTUM}}$$

The use of a 60 percent recovery factor in $\Delta L_{f_{MOM.}}$ was based on integrating positive pressures on the plate undersurface obtained in tests of a two jet fountain.

The pressure measurements on the plate revealed sizeable areas of negative pressures on each side of the fountain's positive pressure zone, between the nozzle exits. This is believed to be caused by a peeling off and recirculation of the outer edges of the fountain back into the free jet and is apparently the major cause of the fountain interference effect. It is a lift loss component which can greatly reduce the fountain positive lift effect.

The fountain interference is expressed as:

$$\Delta L_{fi} = K_{fi} \left(\frac{S_f}{d^2} \right)$$

Where: S_f = surface area between a nozzle and its fountain centerline, and

d = nozzle diameter

The values of K_{fi} were determined from the test array and were correlated with fountain height ratio h/d and nozzle spacing l_f/d.

The net fountain effect for any configuration can then be determined by:

$$\Delta L_{f_{NET}} = \Delta L_{f_{MOMENTUM}} + \Delta L_{fi}$$

The expression derived to calculate $\Delta L_{f_{MOMENTUM}}$ is a function of configuration/jet geometry ratios and height ratio, and incorporates the 60 percent momentum recovery factor.

The direct entrainment induced suckdown force is determined in the Karemaa, reference 18, method essentially by using the Wyatt empirical data correlation previously described.

A comparison of the predicted overall induced lift of a representative V/STOL model computed by summation of these three effects (fountain momentum, fountain interference and entrainment) was made with the model test data and showed excellent agreement.

It was however recognized in reference 18 that additional testing is needed to further define the foutain recovery factor for three and four jet configurations having various spacings, and to obtain additional data to further verify the K_{fi} correlations. Additional comparisons of predicted results with tests of other V/STOL configuration and jet arrangements are also in order. This on-going work is presently being sponsored by ONR.

A considerably more limited data base is available for determination of hover jet induced effects of V/STOL employing rectangular jets. The Louisse and Marshall test and analysis work, reference 15, examined a twin rectangular jet ($AR = 1.83$) configuration in which the jets were oriented both longitudinally and laterally to the free stream. Major findings of the rectangular jet tests were: with the jets oriented laterally, the induced lift loss was comparable to that predicted for a single round jet. No significant fountain effect occurred in this case. With the jets oriented longitudinally (spacing ratio S/D_e varied from 0.5 to 2.0) a sizeable fountain effect occurred sufficient to overcome most of the suckdown effect at low values of H/d_e. A correlation function was developed to predict the pure fountain effect as a function of nozzle spacing and nozzle cant angle. The fountain method of reference 15 is, of course, restricted to low AR rectangular jets. The Vogler tests of twin slotted ($AR = 20$), reference 14, also show a large positive fountain lift effect when the jets are oriented longitudinally. With the jets oriented laterally, there is no evidence of the fountain, although the induced lift loss is considerably lower than for circular jets.

Results from recently initiated NASA Ames sponsored tests of high aspect ratio rectangular nozzles, when available, will be incorporated into the theoretical modeling techniques developed by MAC, as described earlier, to predict hover jet induced effects applicable to arbitrary rectangular jet V/STOL's and augmentor wing V/STOL's.

A composite comparison of jet induced lift effects in hover for several arrangements of jet V/STOL configurations is presented in figure 7 reproduced from reference 19, which generally illustrates the magnitude of induced lift that can be expected from the various alternative jet arrangements. This systematic investigation of a delta wing and body combination started with a basic configuration consisting of four engines arranged in a cluster near the center of the wing-body. The single-jet configuration was obtained by ejecting air from the right rear nozzle only and thus had a larger surface to jet area ratio than the multiple jets configuration. The two rear jets were also tested together, and show a reversal of the lift loss due to ground at very low heights. When the number of jets is increased to four, the lift losses become smaller due to a reduced surface to jet area ratio and due to the fountain. When the spacing between the jet exits is increased, as shown by the other two four-jet configurations, the jets have a

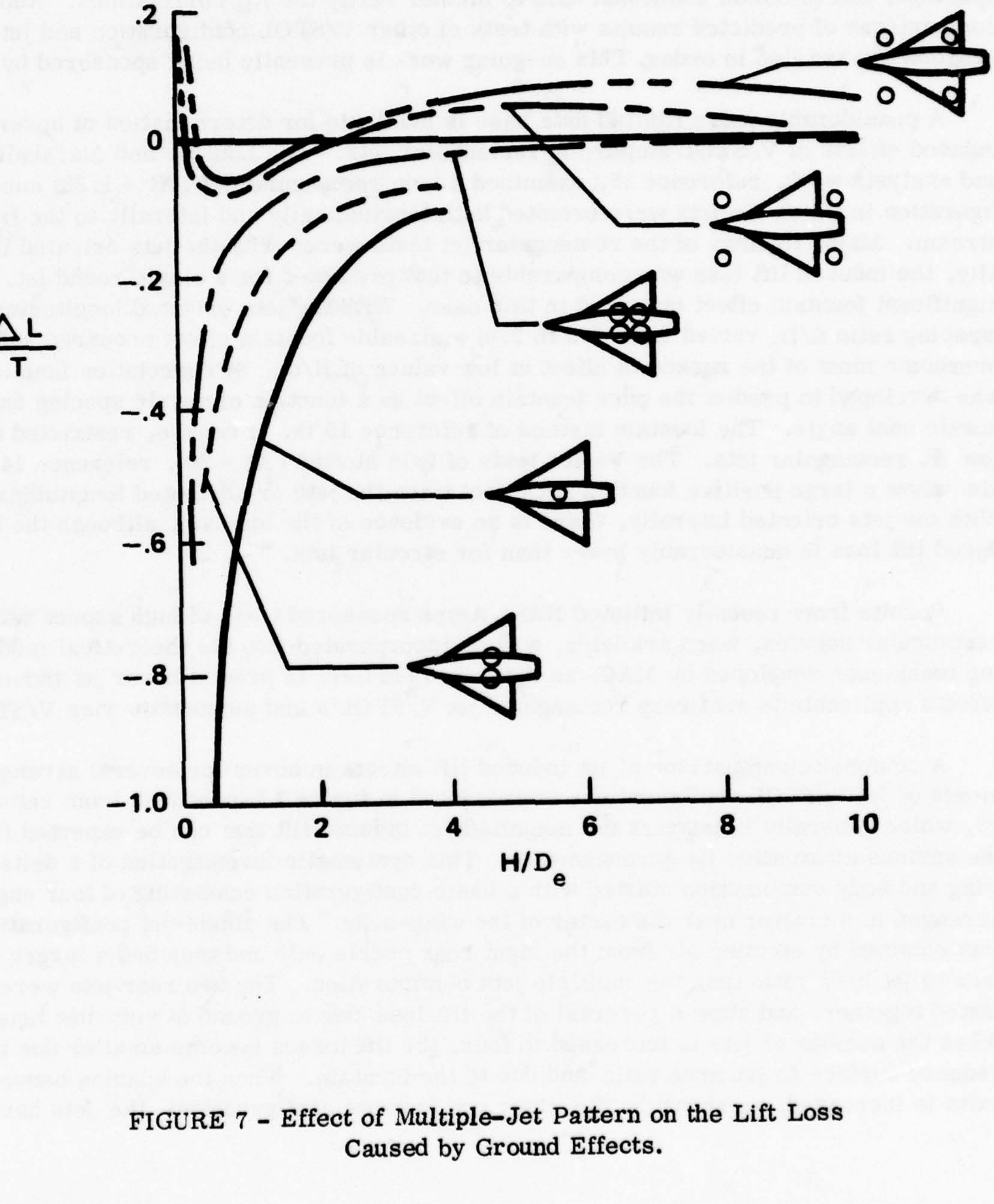


FIGURE 7 - Effect of Multiple-Jet Pattern on the Lift Loss Caused by Ground Effects.

favorable effect on lift at heights above approximately two effective diameters. For a given range of heights, there is a reduction of lift loss with a multiple-jet engine as the exits are spaced farther apart and thus enlarge the model area that experiences favorable pressures from the fountain of jet gases reflected up from the ground.

b. Out of Ground Effect

The early test and analysis work of Margason, reference 13, provides a reasonable empirical basis for estimates of jet induced lift losses of single and closely spaced axi-symmetric jets out of ground effect. The test model was fitted with wings of various sizes and various planforms.

A major finding of the single jet tests was that induced lift losses are substantially increased when the turbulence level of the jet is increased, or when the jet exit profile is non-uniform. Lift losses increase from about 1 percent to nearly 4 percent due to these effects. These effects were also shown to result in a much higher rate of decay of the jet impact pressure with axial distance from the exit. The more turbulent or more skewed jet profile causes a higher entrainment rate creating increased suction pressures on the model undersurface.

A similar more rapid decay characteristic occurs with multiple jets, as compared to a single jet, when the axial distance in the jet is normalized to an equivalent single jet diameter, D_e. This can be interpreted as meaning that the single jet is divided into several smaller discrete jets thus having a greater total jet surface area for mixing with and entraining ambient air. Typical results are shown in figure 8 which is reproduced from reference 13.

Test results were correlated with an empirical expression which gives the induced lift loss as:

$$\frac{\Delta L}{T} = -.009\sqrt{\frac{S}{Aj}}\sqrt{\left[\frac{\partial\left(\frac{q_x}{P_{T,P}-P}\right)}{\partial\left(X/D_e\right)}\right]_{MAX} \Bigg/ \left(\frac{X}{D_e}\right)_{MAX}}$$

where X/De_{max} is the downstream position in the jet where the slope of the impact pressure decay rate is a maximum.

A further refinement to this method is developed in reference 20 to account for the effect of nozzle pressure ratio, given as:

$$\frac{\Delta L}{T} = K\sqrt{\frac{S}{Aj}}\ (NPR)^{-.64}\sqrt{-\left\{\frac{\partial\left(q_x/q_e\right)}{\partial\left(X/D_e\right)}\right\}_{MAX}\Bigg/\frac{X}{D_{e_i}}}$$

where

K = proportionality constant developed in reference 20

$\frac{X}{D_{e_i}}$ = position of maximum decay rate

A difficulty experienced in the application of these methods is knowledge of the actual jet decay characteristics of particular power plants being employed in a vehicle design. However, if the exit profile is known, the decay rate can be estimated using the data of Kleis and Foss, reference 8.

A more recent, easier to apply, OGE lift loss correlation, developed by MAC, uses a direct accounting of multiple jet decay rate effects by introducing the parameter $\Sigma P/D_e$, where P is the sum of the jet nozzle perimeters. Satisfactory correlations of lift loss data from various single and multiple jet tests were made, resulting in the following relationship:

$$\frac{\Delta L/T}{\sqrt{S/A_j}} = .0002528\left[(NPR)^{-.64}\ (\Sigma P/D_e)\right]^{1.581}$$

While this expression does take account of higher overall decay rates of multi-jets, the decay rate of the individual jet dynamic pressures are not considered (doubtless, the jet exit profiles in the various tests were quite uniform). This individual jet decay effect would need to be established from further tests involving a systematic variation of some jet turbulence "characterization".

Of perhaps greater concern for hovering out of ground effect, however, is the effects of cross wind velocities due to vehicle translations or due to winds. Data such as that of Keffer and Baines, reference 21, show substantially higher jet entrainment rates with increasing values of free stream to jet velocity ratio, U_∞/U_j. The higher entrainment rates create increased in-flow velocities and ensuing greater suction pressures on nearby aircraft surfaces.

Some indication of the overall magnitude of jet induced lift loss for single vertical jets in a cross wind is given by the tests of Taylor, reference 22, and Wooler, reference 23. Typical results are presented in figure 9. As shown, the lift loss potential of a

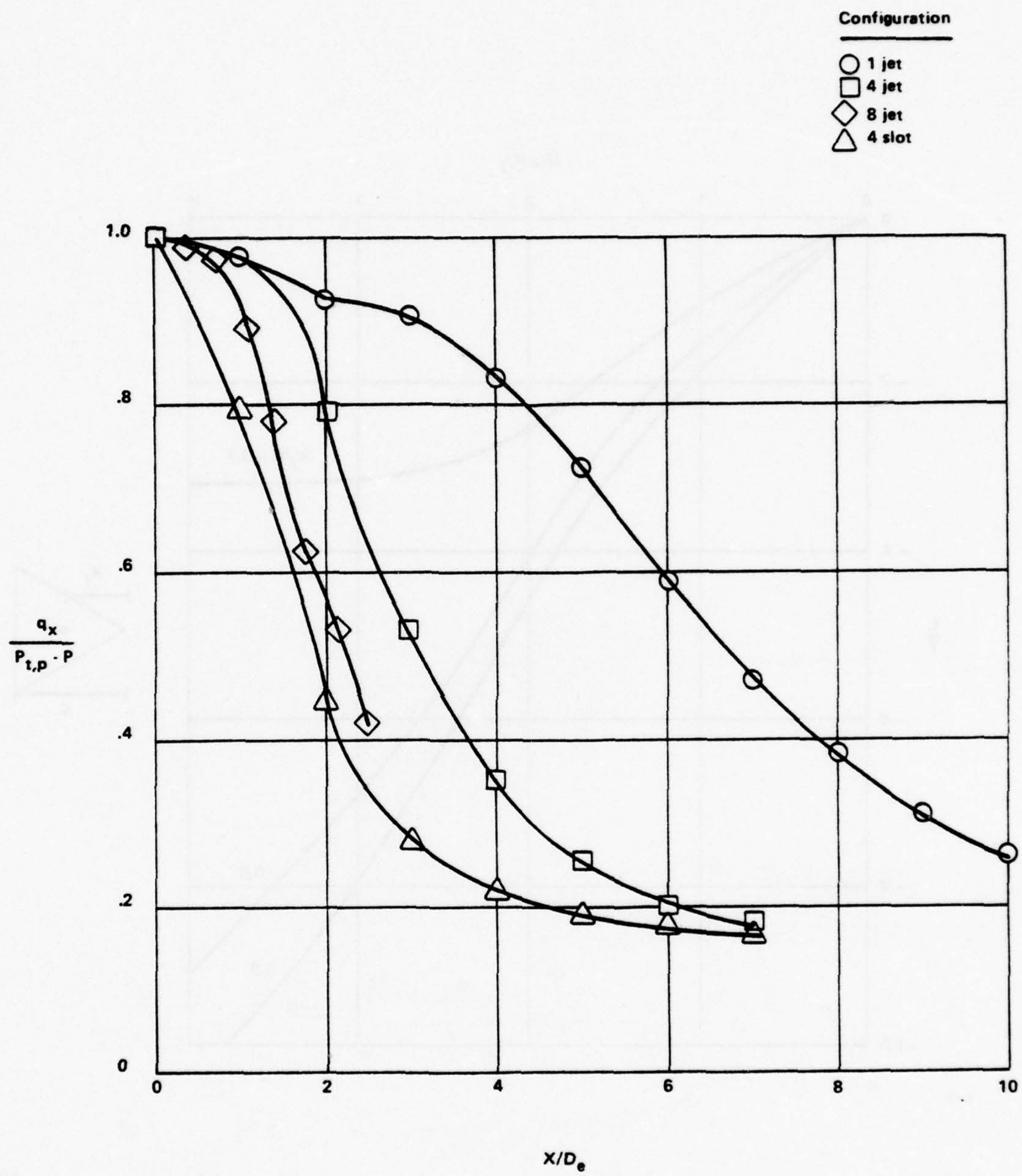


FIGURE 8 - Impact-Pressure Decay for Single-Jet and Multiple-Jet Configurations, $\frac{P_{t,p}}{P} = 1.89$

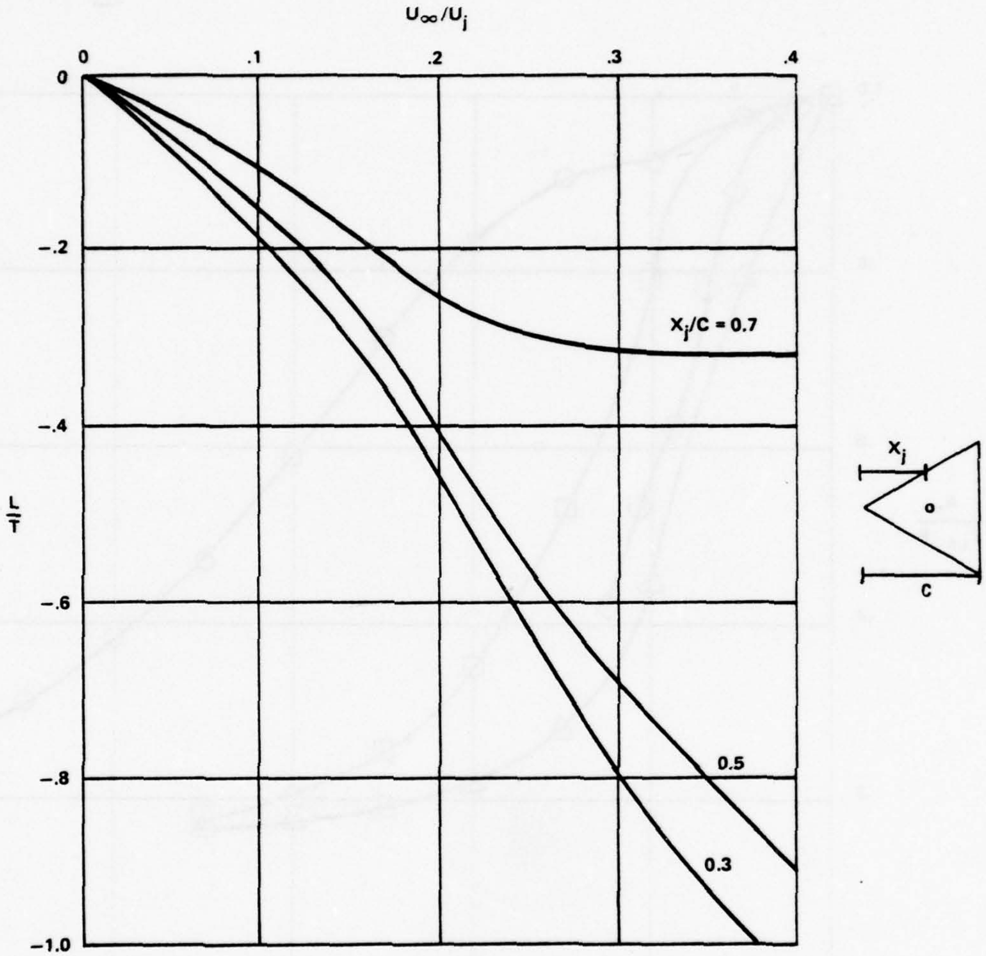


FIGURE 9 - Lift Loss Variation with Velocity Ratio - Single Jet Issuing from Triangular Plate

single jet is of the order of 20 percent at $U_\infty/U_j = .10$ and as high as 30 percent at $U_\infty/U_j = .15$. The point made in all investigations is that the aerodynamic interference of a jet is extremely important and that it is primarily sensitive to the geometric position of the jet, surface-to-jet area ratio and free stream-to-jet velocity ratio. The induced lift loss generally increases with both surface-to-jet area ratio and increasing free stream-to-jet velocity ratio.

Several analytical models have been developed for representing the interference of the jet. They rely on the empirical specification for the jet trajectory, except for the Wooler model, reference 23, which relies on a relation between the entrainment of fluid and the local flow conditions along the jet. Jet vortex models are represented by means of vortex elements with the strengths related to the force acting normal to the jet. The balance between centrifugal force expressed in terms of momentum flux and jet radius of curvature and normal force yields a relation between vortex strength, momentum flux, radius of curvature and free stream velocity.

Jet blockage and entrainment models are represented by a distribution of sinks and doublets as in the Wooler method, reference 23, and the Siclari method, reference 12. The recent analysis by Wooler and Ziegler, reference 24, is based primarily on the Wooler entrainment and blockage model, but also takes account of a non-uniform exit profile. It is applicable to multi-jet induced effects from hover through transition as discussed in detail in Section 2.

For the purpose of developing improved theoretical models of the jet induced flow field of axi-symmetric jets in a cross wind, the recent high quality test data of Weston, reference 25, can provide an improved empirical base for jet modeling, taking account of the important wake separation effects.

The effect of jet efflux profile (jet quality) on jet entrainment, deflection path and induced forces is presently being investigated in tests by Kuhlman, reference 26. Preliminary results indicate a reduction in lift loss with increased jet profile skewness, opposite to the effect observed by Margason for the no wind case.

Very little data is available regarding jet flow field characteristics and induced lift losses for rectangular jets (OGE). Tests of Trentacoste and Sforza, reference 10, and Salter, reference 27, provide some data on entrainment rates and jet decay characteristics applicable to OGE. Entrainment rates of the free jet are generally higher than for circular jets at least for $AR \geq 10$. Jet modeling prediction methodologies applicable to rectangular jets ($AR = 4$) in a cross wind are presently being investigated through model tests and analysis work being conducted by VSD, sponsored by NASA Langley and NADC. Test results have been obtained for rectangular jets oriented both parallel and perpendicular to the flow for jet deflection angles varying from 45 degrees to 105 degrees (measured from horizontal) and velocity ratios from .1 to .25. Results of these tests and jet math models will be presented in a forthcoming NASA report.

c. Summary of Hover Prediction Methods

A reasonably good data base and empirical formulations are available for predictions of lift loss due to entrainment effects, both IGE and OGE, of axi-symmetric jet configurations. A more limited base is available for rectangular jet configurations but test programs are in progress in this area. The synthesis of computer programs which mathematically model the empirically derived entrainment properties of jets IGE and OGE and compute induced effects on arbitrary multi-jet V/STOL configurations are also being developed.

However, a major deficiency exists both in available data base and corresponding math modeling capability relative to the "fountain" induced effects. A very limited amount of testing has been carried out to determine fountain effects. In most tests, the fountain flow properties and fountain induced loads were not directly determined, but are only inferred from the overall force measurements. However, ongoing work by Karemaa, reference 18, sponsored by ONR holds considerable promise for isolating the direct fountain effect and its intereference effects.

Knowledge of fountain flow and impingement properties and the configuration arrangements that take advantage of its favorable induced upload offer a major return in minimizing propulsion system size and weight in V/STOL designs. In addition to the test and analysis work of Karemaa and that planned by MAC for inclusion into their computerized prediction methodology it is felt that additional test efforts should be undertaken to further investigate configurational features that can enhance the favorable fountain effect. Work of this type has been carried out on the AV-8A Harrier to improve lift-off capability of that specific design. This type of work should also be done on more generalized jet V/STOL configurations to advance the knowledge of propulsion induced effects in hover and techniques to provide favorable effects.

A further area of concern in jet induced aerodynamics prediction capability is the validity of using potential flow models for jet V/STOL aircraft hovering in close ground proximity, as was discussed in the section on computerized techniques.

2. Propulsion Induced Aerodynamics in Transition Flight

The V/STOL transition flight regime covers the velocity range from low speed hover to the sustained velocity required for fully wingborne flight. Jet exhaust effects have a dominant influence on aerodynamic characteristics in this regime, inducing large forces and moments on the aircraft. Lift losses can exceed 20 percent of the static jet thrust as shown in figure 10 depending upon jet number and location. These jet effects involve the interaction of the jet and free-stream flow and are primarily the result of four viscous flow phenomena - jet blockage, wake separation, entrainment, and vortex generation. Blockage effects result from the free stream experiencing an effective boundary of high jet penetration airflow, inducing a pressure distribution on the surface

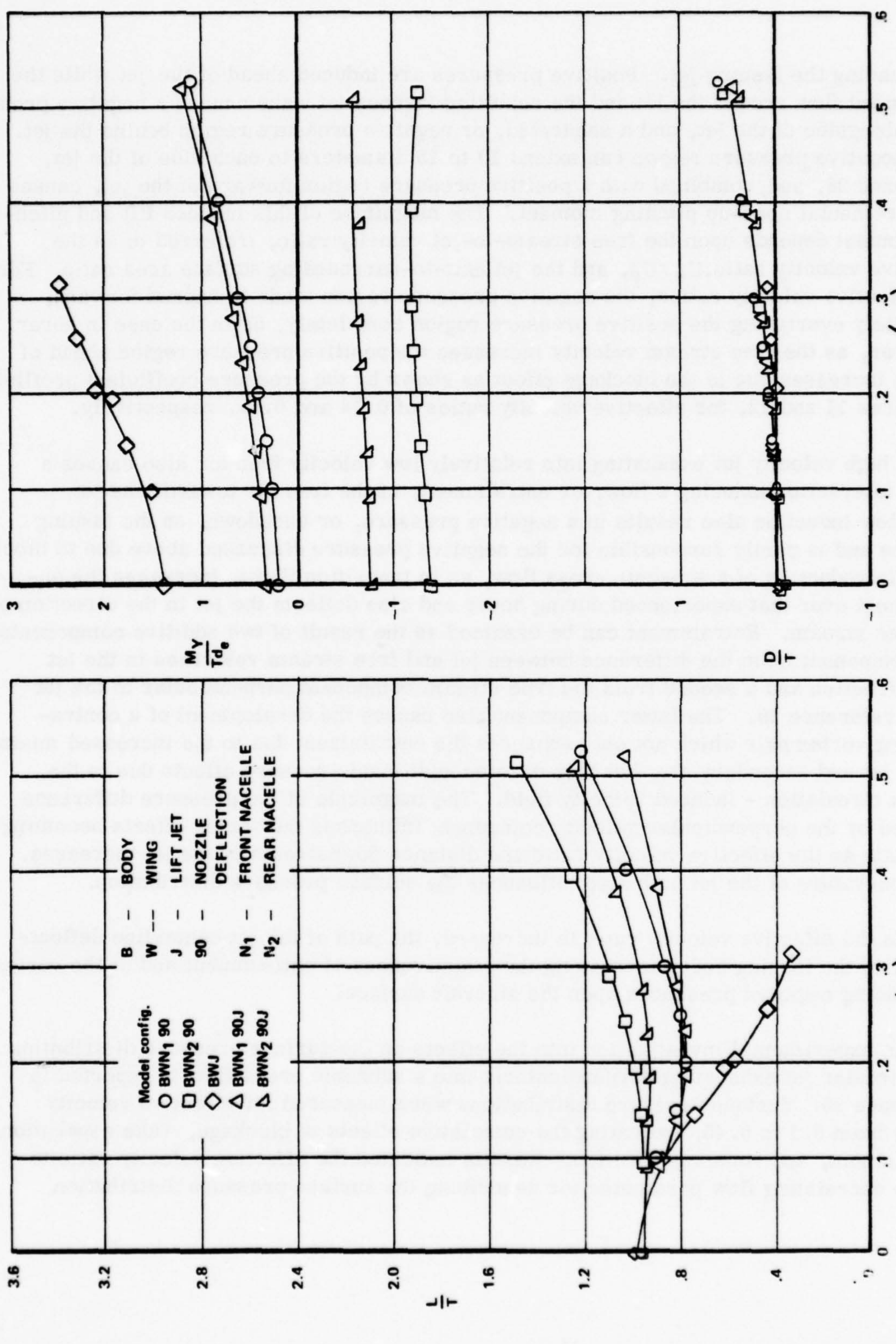


FIGURE 10. Effect of Thrust Configuration on Longitudinal Aerodynamic Characteristics (Ref. 37)

surrounding the issuing jet. Positive pressures are induced ahead of the jet while the high speed flow around the jet and the resulting viscous jet wake causes a negative pressure alongside of the jet, and a separated, or negative pressure region behind the jet. This negative pressure region can extend 10 to 15 diameters to each side of the jet, reference 28, and, combined with a positive pressure region forward of the jet, causes an incremental nose-up pitching moment. The magnitude of this induced lift and pitching moment depends upon the free stream-to-jet velocity ratio, (referred to as the effective velocity ratio, U_∞/U_j), and the jet exit-to-surrounding surface area ratio. For low effective velocity ratios, the negative pressure region tends to expand forward, ultimately overtaking the positive pressure region completely, as in the case in hover. However, as the free stream velocity increases the positive pressure region ahead of the jet increases due to the blockage effect as shown by the pressure coefficient profiles in figures 11 and 12, for effective velocity ratios of 0.14 and 0.45, respectively.

A high velocity jet exhausting into relatively low velocity free air also causes a shear interaction inducing a flow, or entrainment, of the free air towards the jet. This flow induction also results in a negative pressure, or suckdown, on the issuing surface and is partly responsible for the negative pressure discussed above due to blockage. Introduction of a subsonic cross flow, as in transition flight, increases the entrainment over that experienced during hover and also deflects the jet in the direction of the free stream. Entrainment can be assumed as the result of two additive components, one component from the difference between jet and free stream velocities in the jet axis direction and a second from the free stream component perpendicular to the jet axis, reference 29. The latter component also causes the development of a contra-rotating vortex pair which not only enhances the entrainment due to the increased mixing of the jet and secondary air, but also creates additional pressure effects due to the vortex circulation - induced velocity field. The magnitude of the pressure difference created by the perpendicular velocity component influences the vortex effects becoming dominate as the effective velocity ratio and distance downstream of the jet increases. This curvature of the jet path also influences the surface pressure distribution.

As the effective velocity ratio is increased, the path of the jet centerline deflects closer to the issuing body, increasing the effectiveness of entrainment and of the vortex in inducing negative pressures upon the aircraft surface.

An experimental investigation into the effects on the surface pressure distribution of a circular jet exhausting perpendicularly into a subsonic cross flow is reported in reference 25. Surface pressure distributions were measured for effective velocity ratios from 0.1 to 0.45, indicating the cumulative effects of blockage, wake separation, entrainment, and vortex generation. Results indicated the effective velocity ratio to be the correlating flow parameter for describing the surface pressure distribution.

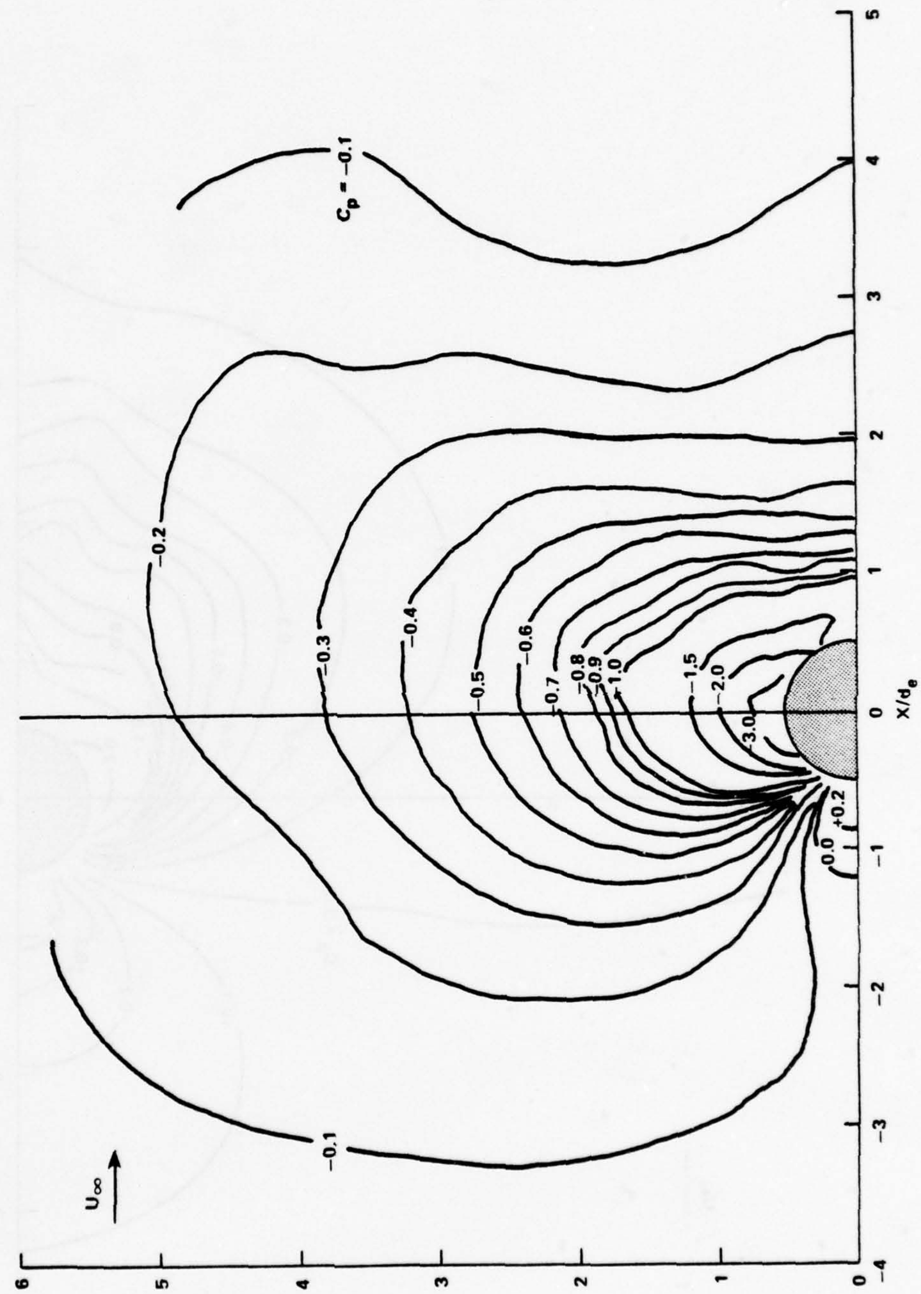


FIGURE 11. Surface Pressure Coefficient Contours for a Single Jet Issuing Normal to Free Stream, $V_e = 0.14$

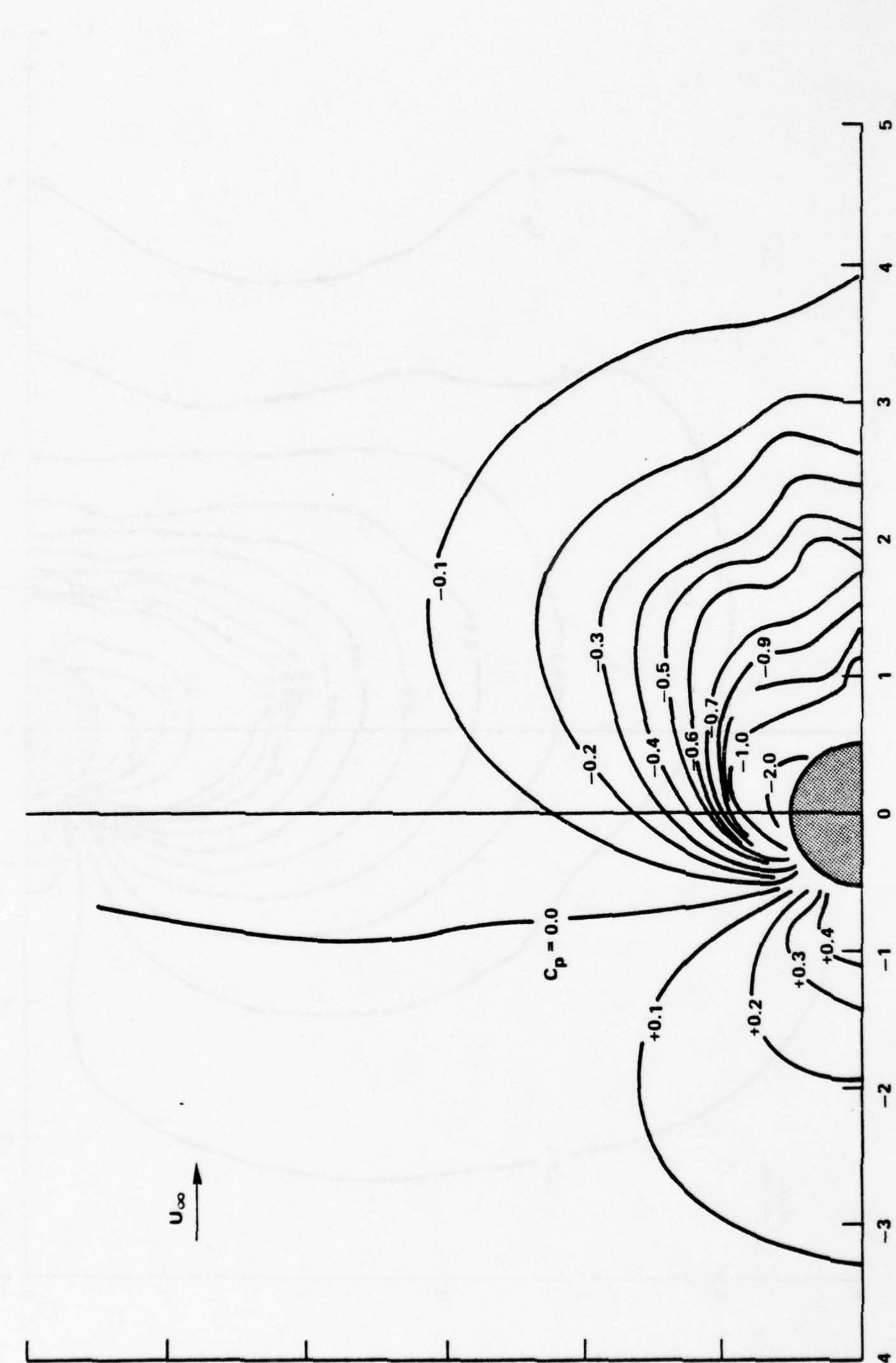


FIGURE 12. Surface Pressure Coefficient Contours for a Single Jet Issuing Normal to Free Stream, $V_e = 0.45$

These viscous phenomena are highly configuration dependent being sensitive to geometric position of the jet and the jet-to-surface area ratio in addition to the effective velocity ratio. Figure 10 illustrates this dependency showing test results of a VTOL model with various jet arrangements. Data indicate that the lift jet in the fuselage (BWJ), having a relatively low jet-to-surface area ratio, experiences the large negative pressure on the surface behind the jet due to wake separation and entrainment at low speeds, and the increasing influence of the vortex at higher speeds resulting in decreasing lift with increasing effective velocity. The aft wing deflected jet configuration (BWN_290), having no area aft of the jet for negative pressures to act, experiences the increasing positive pressures on the surface forward of the jet due to blockage and enhanced flow over the wing upper surface resulting in increasing lift with increasing effective velocity.

A significant investigation, reference 30, further demonstrating the sensitivity of interference effects to jet exhaust location systematically varied the location of the jet from several wing chord lengths ahead to several chord lengths behind the wing along with various vertical locations about the wing. Figure 13, taken from reference 19, shows typical results of this investigation and illustrates the effects discussed above. The results indicated that all jet locations ahead of the wing cause detrimental effects on wing lift.

Minimum lift interference occurred below the wing near the midchord. In locations aft of the midchord, favorable lift interference occurred being more pronounced near the wing flap. The favorable interference effects experienced aft of the wing were unaffected by vertical movement.

Various V/STOL model designs have been experimentally investigated to determine the jet interference effects and to extend the knowledge of configuration types which minimize the detrimental effects or produce favorable effects. A series of investigations of a VTOL model with single and multiple circular or slotted jets are reported in references 14, 31 and 32. Lift and pitching moment data were measured for a variety of conditions both in and out of ground effect. The slotted jet configuration showed reduced lift losses compared with the circular jets as shown in figure 14. Increased lateral spacing resulted in a further reduction in lift losses and even a lift gain in ground effect, with decreased nose-up pitching moments. Figure 15 indicates that the difference in measurements taken with a moving and stationary ground plane were generally small for both the circular and slotted jet configurations.

a. Out of Ground Effect

Several analytical techniques have been developed using theoretical/empirical formulations to determine the aerodynamic interference of jets on V/STOL aircraft. Because of the turbulent nature of the jet exhausting into the free stream, various empirical solutions, required to determine the jet induced velocity, are combined with theoretical potential flow solutions to obtain the pressure distribution and resulting forces and moments on the aircraft.

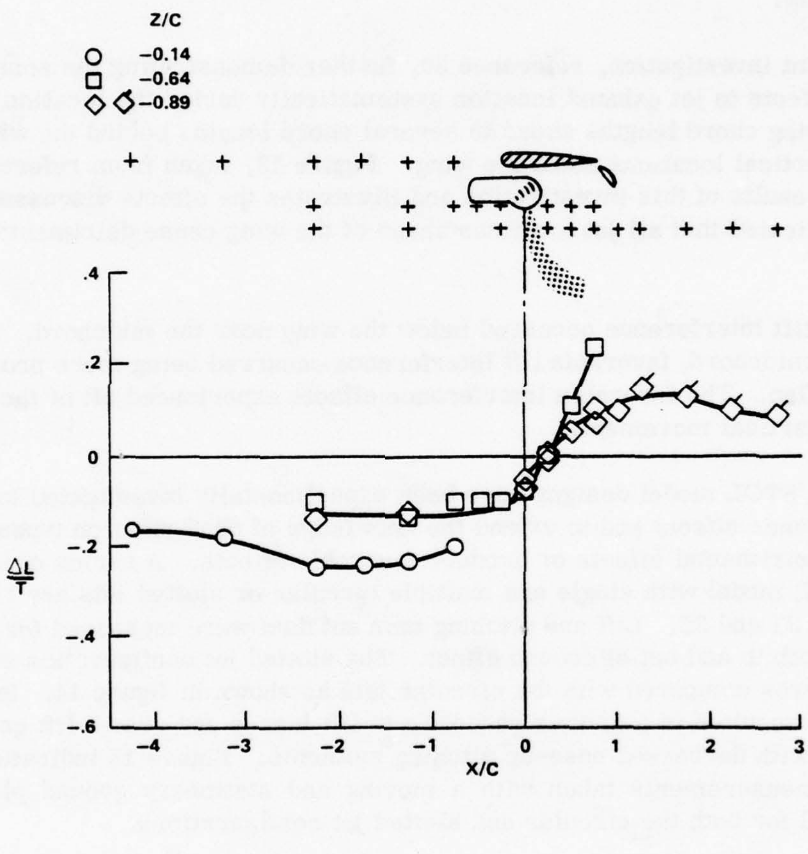


Figure 13. Increments of Interference Lift During Transition Flight, Showing the Effect of Varying the Chordwise Location of the Jet

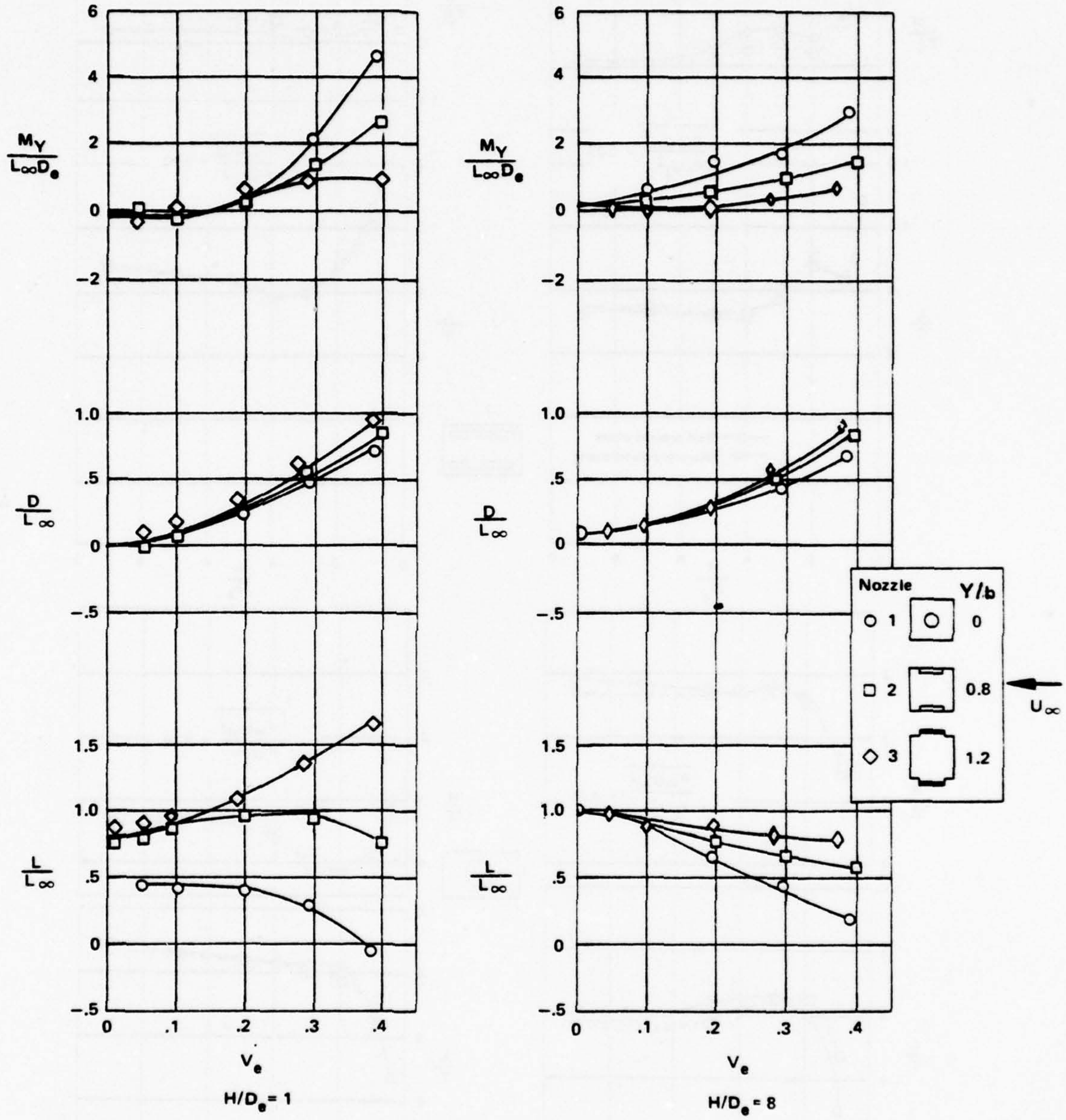


FIGURE 14. Effects of Spanwise Location of Slotted Jet Configurations on Longitudinal Aerodynamics Both In and Out-of Ground Effect Compared With a Circular Jet Configuration

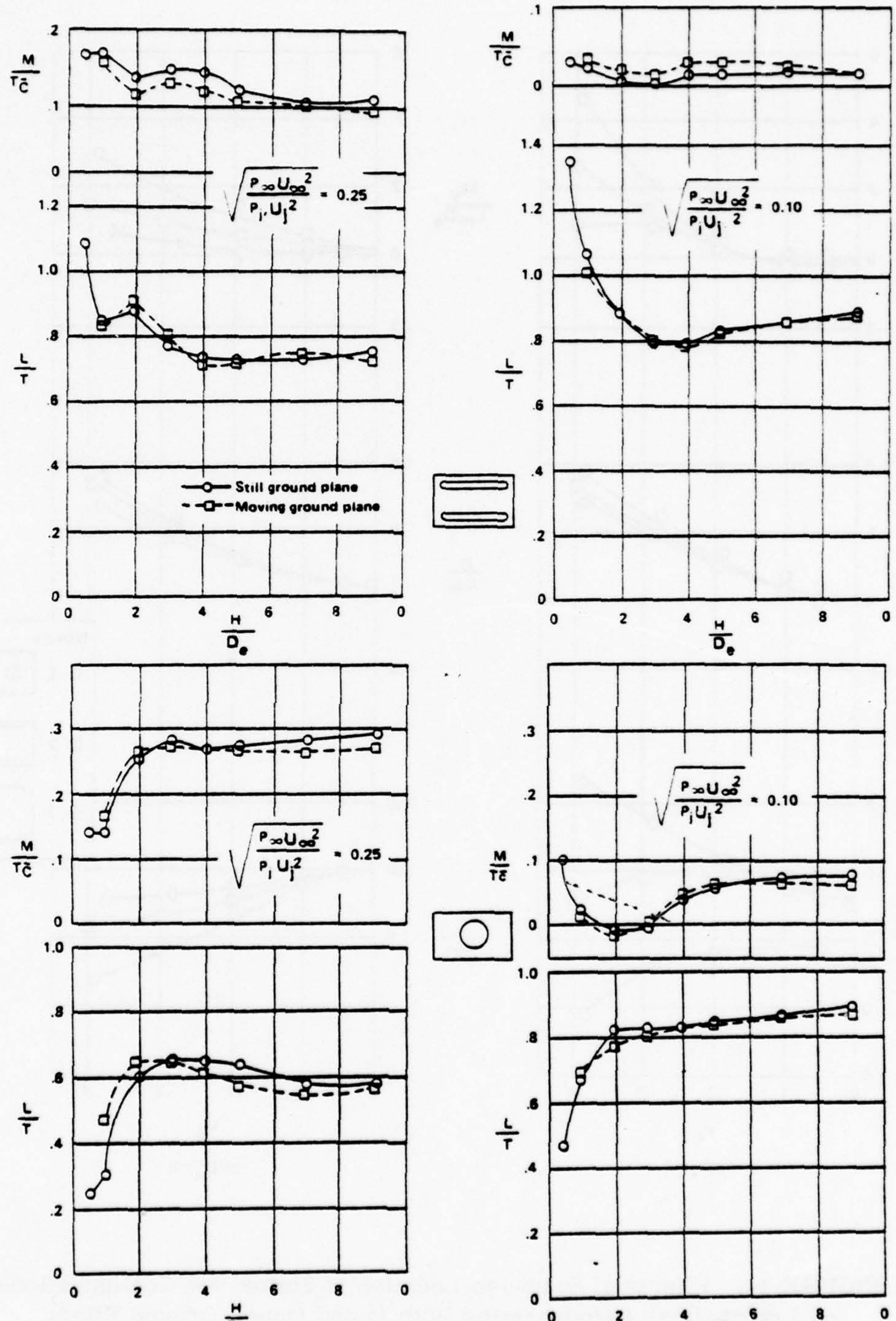


FIGURE 15. Comparison of Effects of a Still and a Moving Ground Plane for Various Forward Speeds through a Range of Model Heights at $\alpha = 0°$

Potential flow analysis requires modeling of the aircraft through the use of a variety of source and vortex distributions. The Hess paneling and vortex lattice paneling methods are two of the most widely used techniques. As discussed in the section concerning computerized techniques, various combinations of jet and aircraft modeling methods establish basic differences, in capabilities and limitations to account for blockage, wake separation, entrainment, and vortex generation.

One well known technique is that developed by Wooler, et. al., reference 23, a semi-empirical method capable of calculating the propulsion induced aerodynamics for one or more circular jet configurations at various angles of attack and sideslip. This method is based upon earlier work, reference 33, which modeled the single, circular jet exhausting into a quiescent atmosphere. Mass entrainment is first developed from a dimensional analysis characterized with empirically derived constants. The jet path is then obtained, treating the force on the jet boundary as a cross flow drag. This drag is based on an assumed elliptical jet cross section whose major to minor axis ratio increases linearly from one at the jet exit to four at some distance along the jet axis, being a function of free stream to jet velocity ratio. Solution of the continuity and momentum equations results in the jet path curvature. By replacing the jet with a distribution of sinks and doublets along the calculated jet path the induced velocity field of the jet is obtained. The sink distribution and strengths are made proportional to the mass entrainment of the jet as determined above, with a distribution of doublets representing the jet blockage effect. The total interference velocity is then obtained by adding the induced velocity components of the sink and doublet distributions. Lifting surface theory, reference 34, is used to predict the downwash at the lifting surface satisfying the boundary condition of no flow through the surface. Velocities induced by the lifting surface are added to the velocities induced by the jet to give the final velocity distribution on the lifting surface.

The method in reference 23 results from an extension of reference 33, and includes multiple, circular jets with angle of attack and sideslip, and adds a mapping transformation technique to calculate the jet induced velocity flow around the fuselage. Analysis of the multiple jet configurations assumed that a leading jet develops independently of the downstream jet until intersection occurs. Downstream jets were assumed to behave as single jets developing into a cross flow of reduced dynamic pressure based on the amount of interference of the leading jet due to its relative position.

Data from a wind tunnel investigation conducted in support of the aerodynamics prediction method development was used to substantiate the assumptions made in the analytical jet model, and to derive the formulation for the effective dynamic pressure which the downstream jet "sees" as a result of the blockage of the cross flow by the upstream jet. This data, reported in reference 35, consists of surface pressure distributions for one, two, and three circular jet configurations exhausting at various angles into a crossflow for an effective velocity ratio range of 0.1 to 0.3. Jet path and decay

characteristics were determined for the one and two jet configurations with sideslip and spacing effects obtained for the two and three jet arrangements. The data also showed that a jet decays more rapidly when exhausting into a crossflow, indicating that the crossflow significantly increases jet entrainment.

Figures 16 and 17 compare the predicted pressure distributions for one and two-jet configurations, with test data of reference 35. Good correlation is shown in both cases except in the wake region which begins approximately 135 degrees from the front. This indicates the failure of the technique to account for the jet viscous wake effects causing the separated region behind the jet. Good correlation is shown for the predicted jet path as shown in figure 18 for the one and two jet configurations, with test data of reference 36.

Reference 37 contains the results of a test program which compares the results of the Wooler aerodynamic prediction method with model test results. A vectored thrust V/STOL configuration with one lift jet and two vectored thrust engine simulators was tested to obtain longitudinal and lateral-directional aerodynamic characteristics. The vectored thrust engines could be positioned beneath the wing at stations $0.11\bar{c}$ or $1.11\bar{c}$. Reference 30 presents the comparison of this test data with theoretical predictions from Wooler's technique. As shown in figure 19, the lift interference on the fuselage due to lift jets is far greater than indicated by the Wooler prediction technique, further demonstrating again the failure of this method to account for the separated region behind the jet. However, for jet locations having reduced surface area aft of the jet, test results showed good agreement in magnitudes and trends as shown in figure 11 of reference 38.

A further improvement on this analytical technique is presented in reference 24. Procedures were developed to determine the induced flow field from stratified jets and to improve the treatment of multiple jets by accounting for the mutual interference of each jet on the other. Three types of jet exit velocity stratification were considered: annular nozzles with a relatively high velocity core representative of turbofan engine exhaust, annular nozzles with relatively low velocity core representative of a lift fan engine, and a vaned nozzle which is considered for vectored thrust concepts. The stratified jets are treated as equivalent uniform profile jets by determining an effective jet exit velocity parameter (jet exit to free stream velocity rates) and an effective jet exit diameter of the equivalent ideal nozzle, which has the same mass flow and thrust as the stratified jet. The predicted surface pressure distributions using this method are shown in figure 20 for the high velocity core and indicate good correlation with the test data of references 35 and 39. This data obtained in support of the analysis procedures for stratified jets verified the approach of using an ideal equivalent nozzle, and also verifies their improved treatment of multiple jets in a cross flow.

However, for the closely spaced jet configurations in sideslip, differences between theory and test were significant. The downstream jet, seeing less blockage of crossflow from the upstream jet, now exerts a stronger influence on the development of a

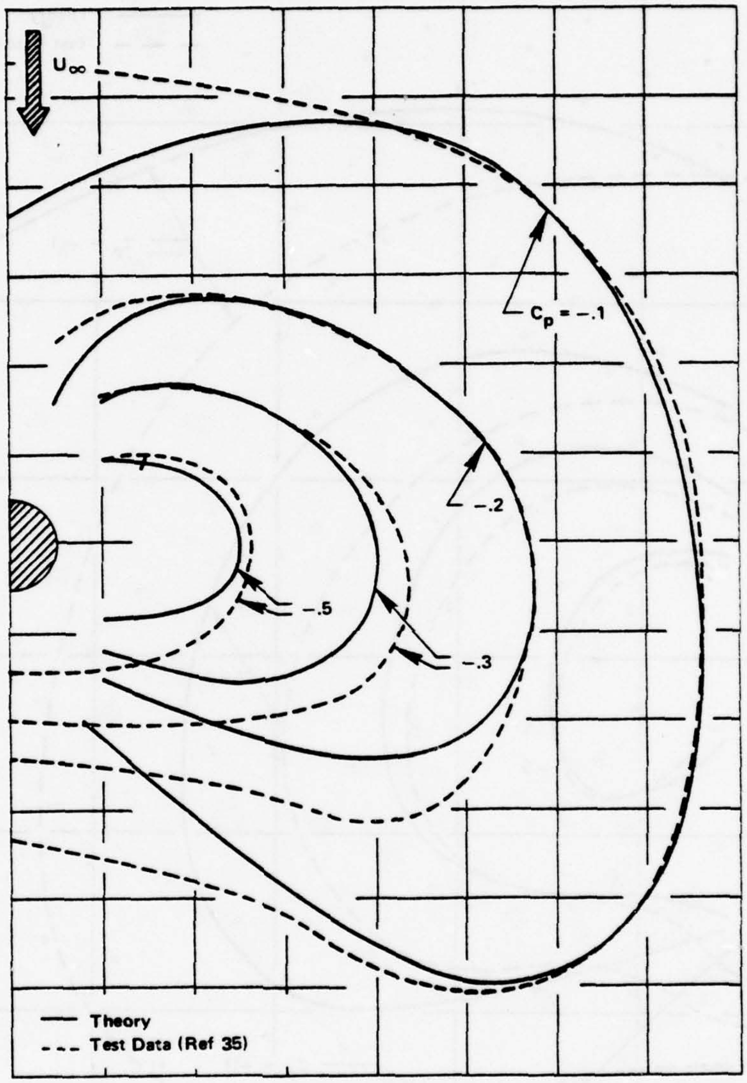


FIGURE 16. Pressure Distribution Around a Single Jet Exhausting at an Angle $\delta_j = 90°$ into the Freestream $U_\infty/U_j = .125$)

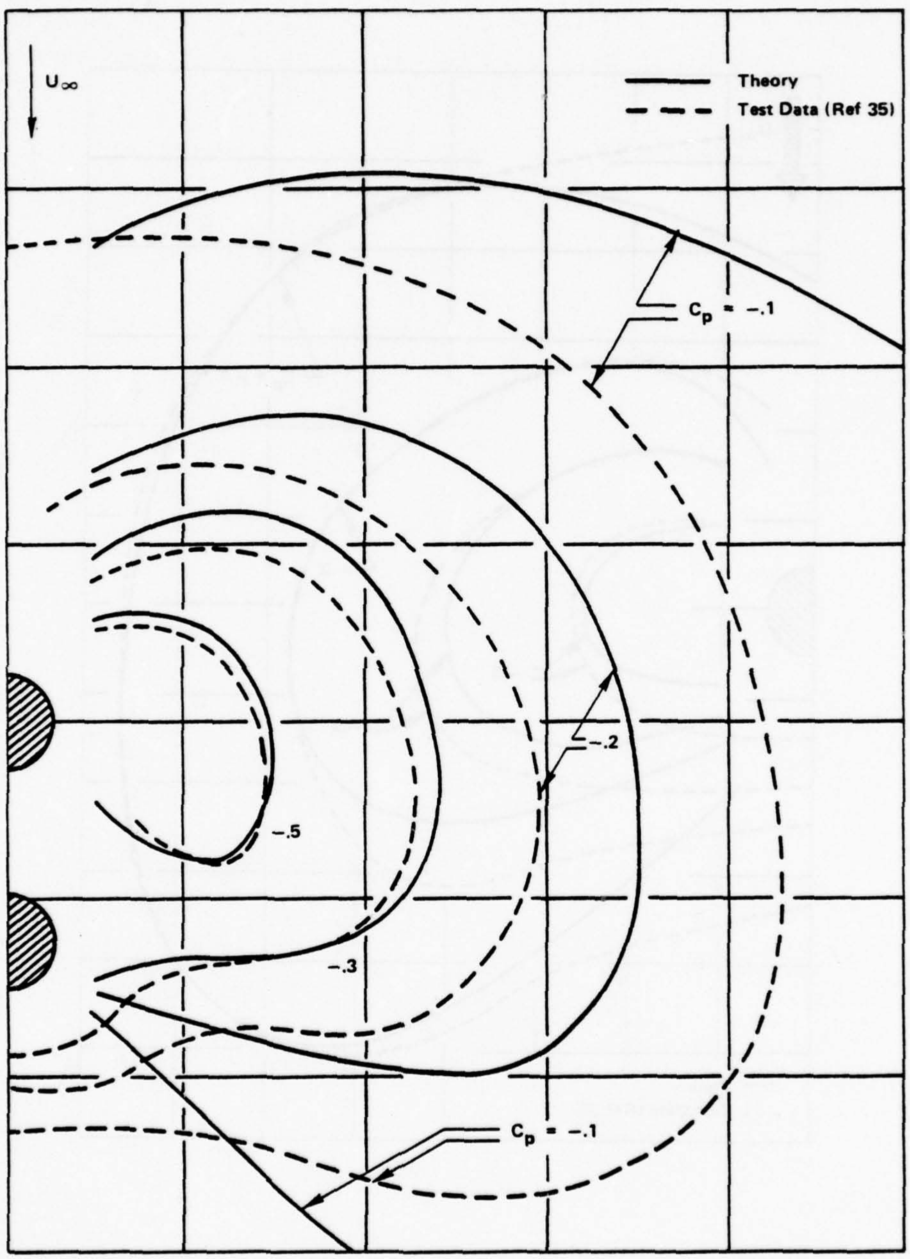


FIGURE 17. Pressure Distribution Around Two Jets at a Spacing of 2.5 Diameters (U_∞ / U_j = .125)

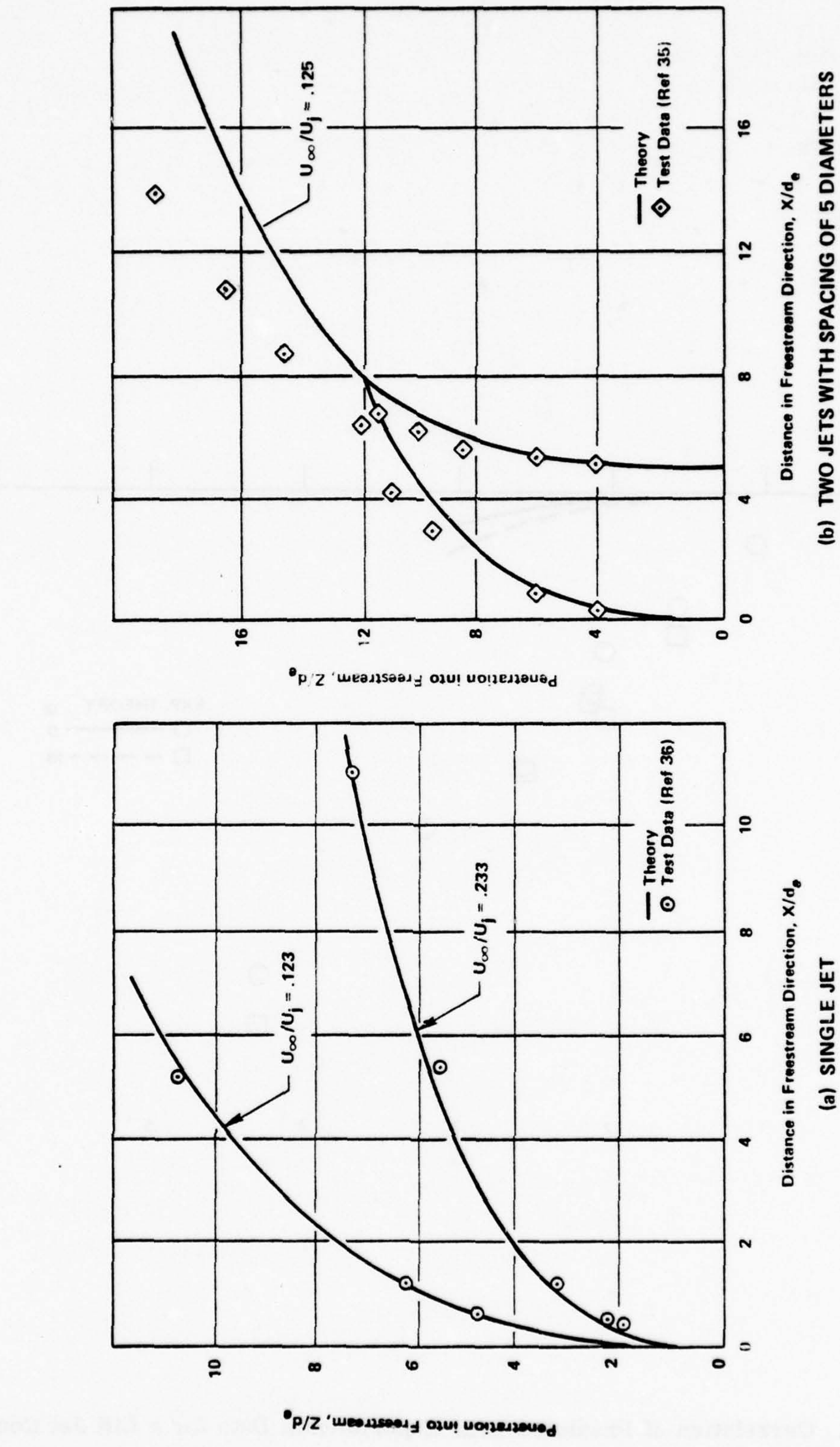


FIGURE 18. Centerlines of Jets Exhausting Normally into the Freestream

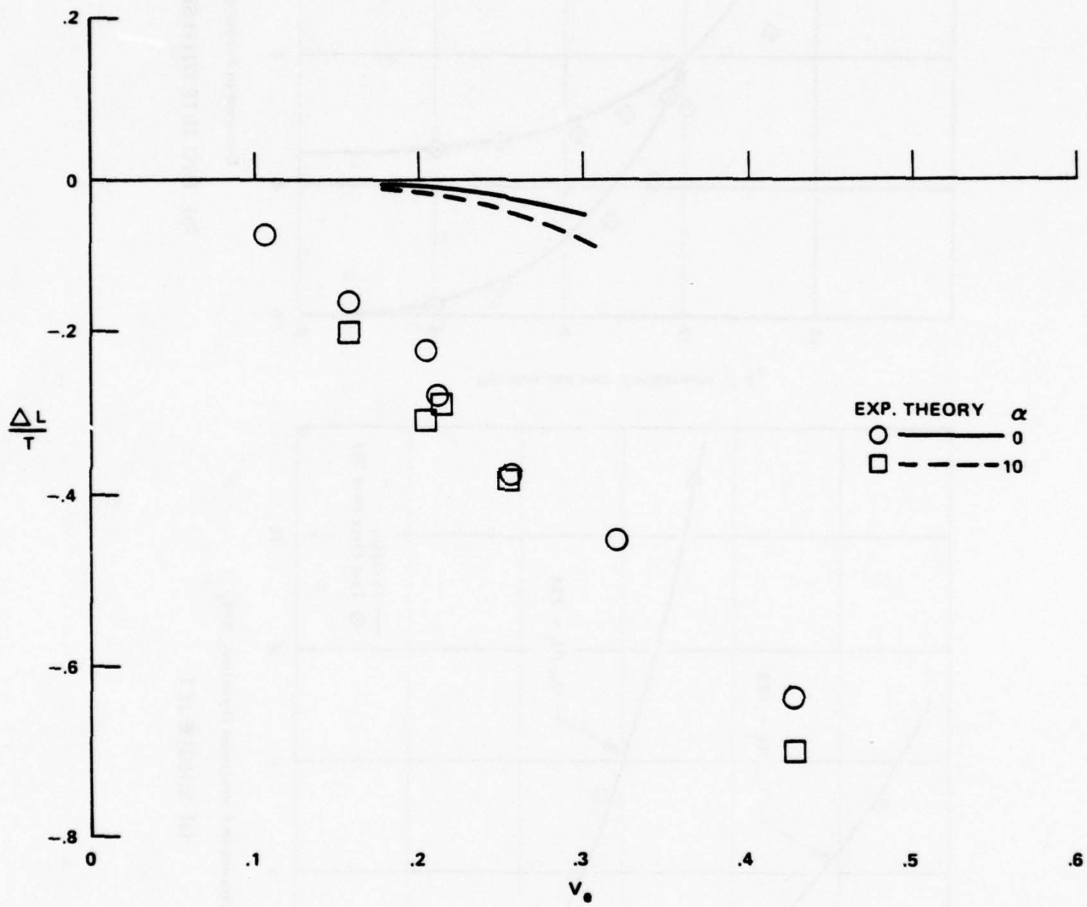


FIGURE 19. Correlation of Predicted with Experimental Data for a Lift Jet Configuration

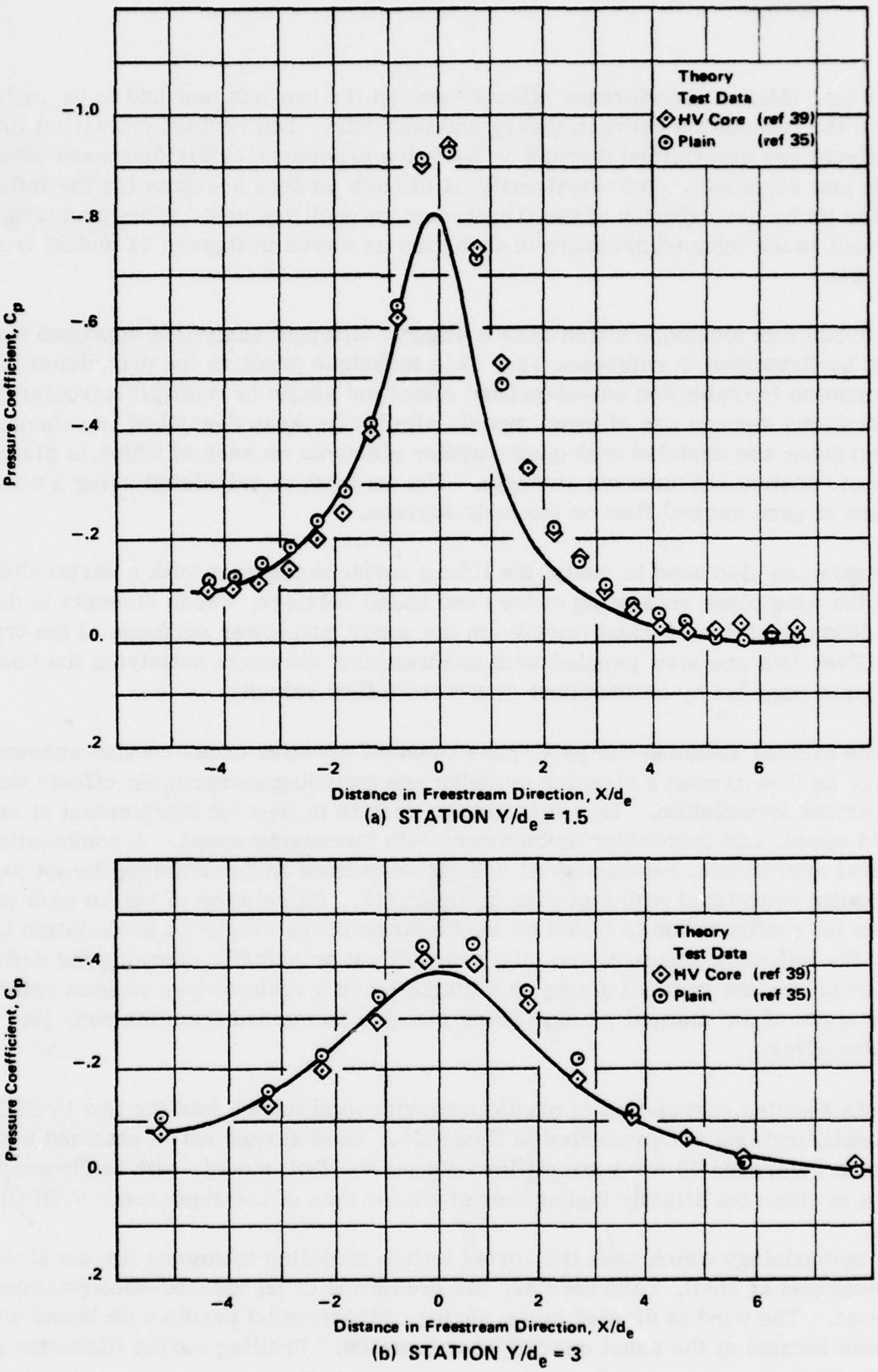


FIGURE 20. Induced Pressure Variation for a High Velocity Core Jet ($U_\infty/U_j = 0.125$)

merged jet. Mutual interference effects between the two jets now had to be included to improve the calculation between theory and test data. The revised mutual jet interference effects are determined through an iterative procedure by dividing each exhausting jet path into segments. Individual analysis of each jet then accounts for the influence of the other jet by perturbation of the freestream on each segment. This provides an improvement in the induced pressure distribution as shown in figures 21 and 22 from reference 24.

A prediction technique which uses a slightly different analytical approach was developed by Grumman in reference 12. This technique predicts the propulsion induced aerodynamics in transition out-of-ground effect for single or multiple-circular jet configurations through use of panel models similar to those described in reference 40. Body surfaces are modeled with quadrangular elements on each of which is placed a source of constant but unknown strength. The strength is calculated using a boundary condition of zero normal flow on the body surface.

Panels are also used to model the lifting surfaces together with a vortex distribution in the wing plane consisting of free and bound vortices, whose strength is determined by the Kutta condition of equal velocity on the upper and lower surfaces at the trailing edge. Free jets are also paneled with quadrangular elements satisfying the boundary constraints imposed by entrainment (non-zero inflow velocity).

This method assumes the jet to have constant circular cross section accounting for blockage as flow around a circular cylinder and including entrainment effects through an empirical formulation. This formulation results in free jet entrainment at zero forward speed, and increasing entrainment with increasing speed. A combination of empirical approaches, references 41 and 42, were used in determining the jet path with results correlated with test data in figure 23. Calculation of the jet path for the multiple jet configuration is based on modification of the single jet formulation to satisfy the following assumptions: the rear jet not principally changing the deflection of the front jet; the rear jet acting as a single jet in a reduced free stream velocity; and the slope of the merged jet axis being mainly determined from the rear jet characteristics.

Data showing correlation of predictions with wind tunnel data for two V/STOL aircraft configurations are presented in figure 24. Good agreement is obtained with the data from reference 30 for a simplified twin jet V/STOL model, with fairly good comparison in slope but slightly higher magnitude for data of the supersonic V/STOL model.

A methodology which uses the vortex lattice modeling technique for the aircraft was developed at MAC, reference 43, for prediction of jet induced aerodynamics in transition. The wind is divided into a series of trapezoidal panels with bound vortex filaments located at the panel quarter chord station. Trailing vortex filaments are

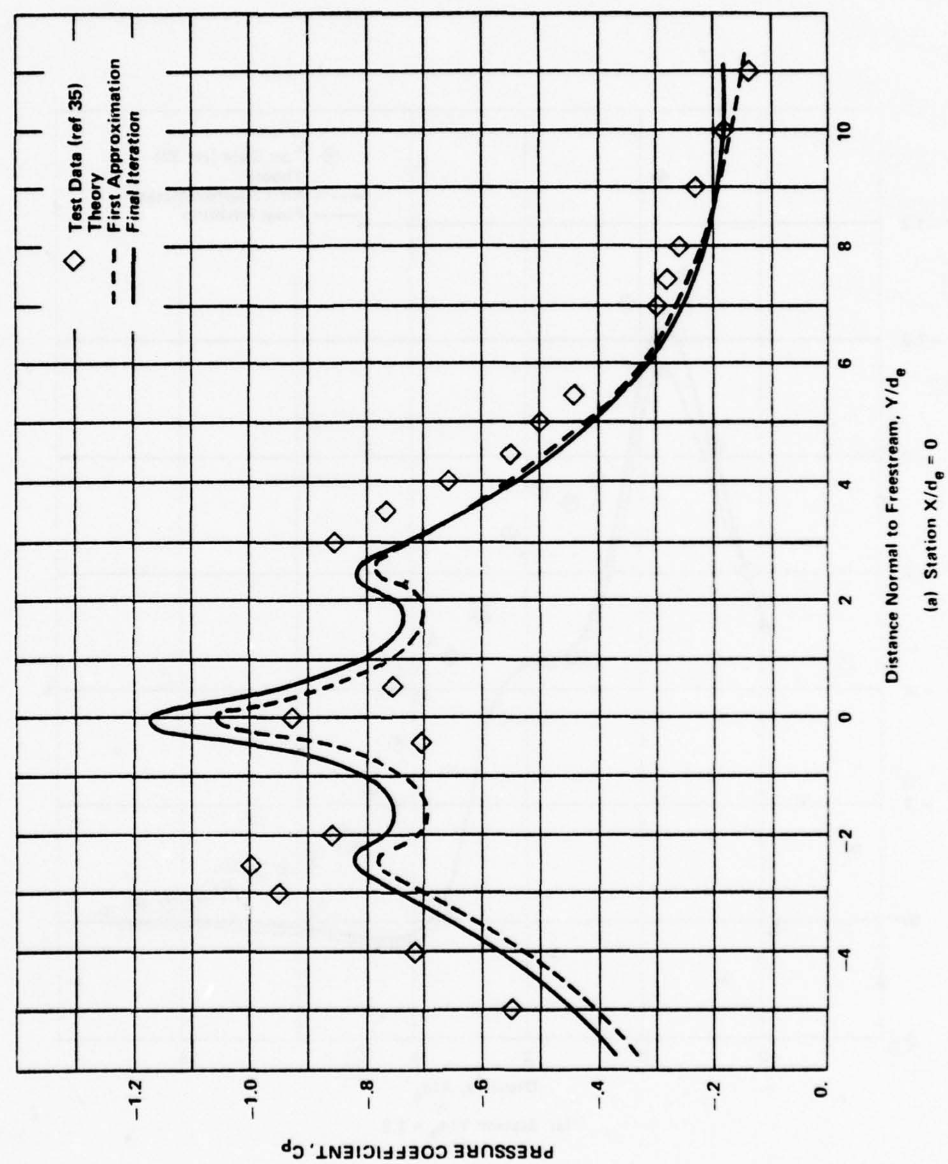
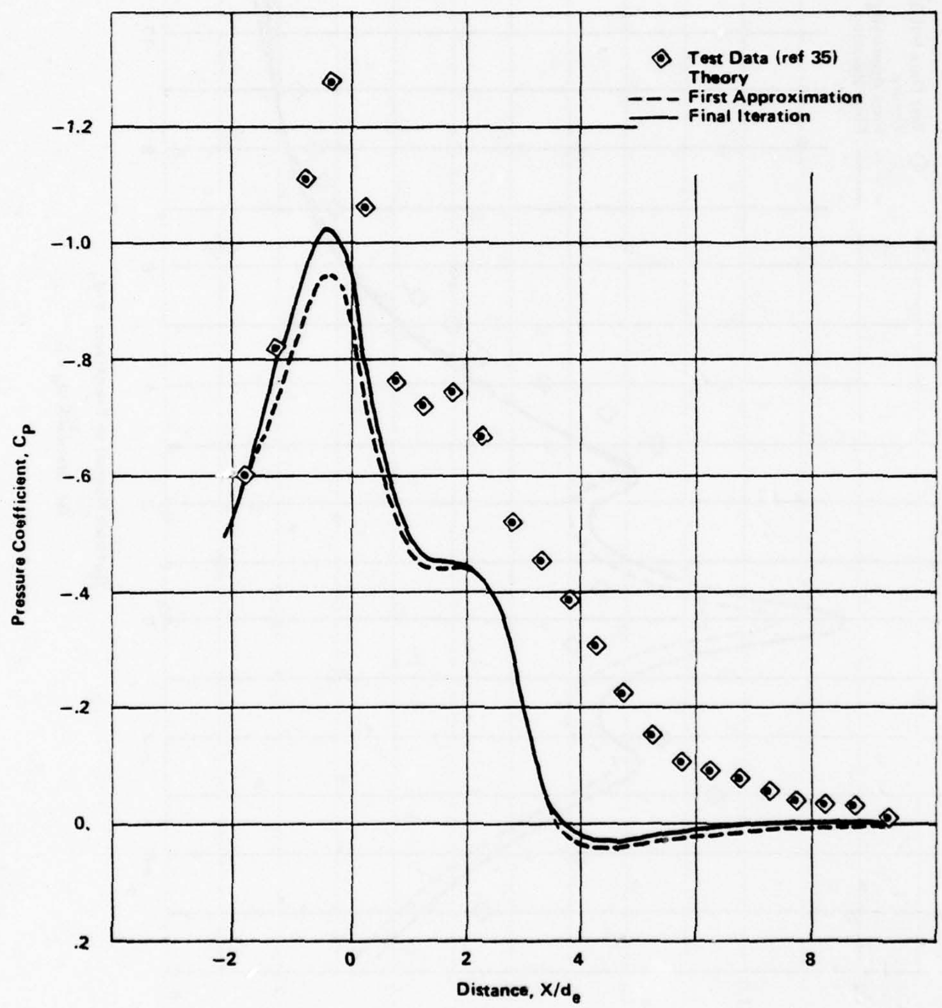
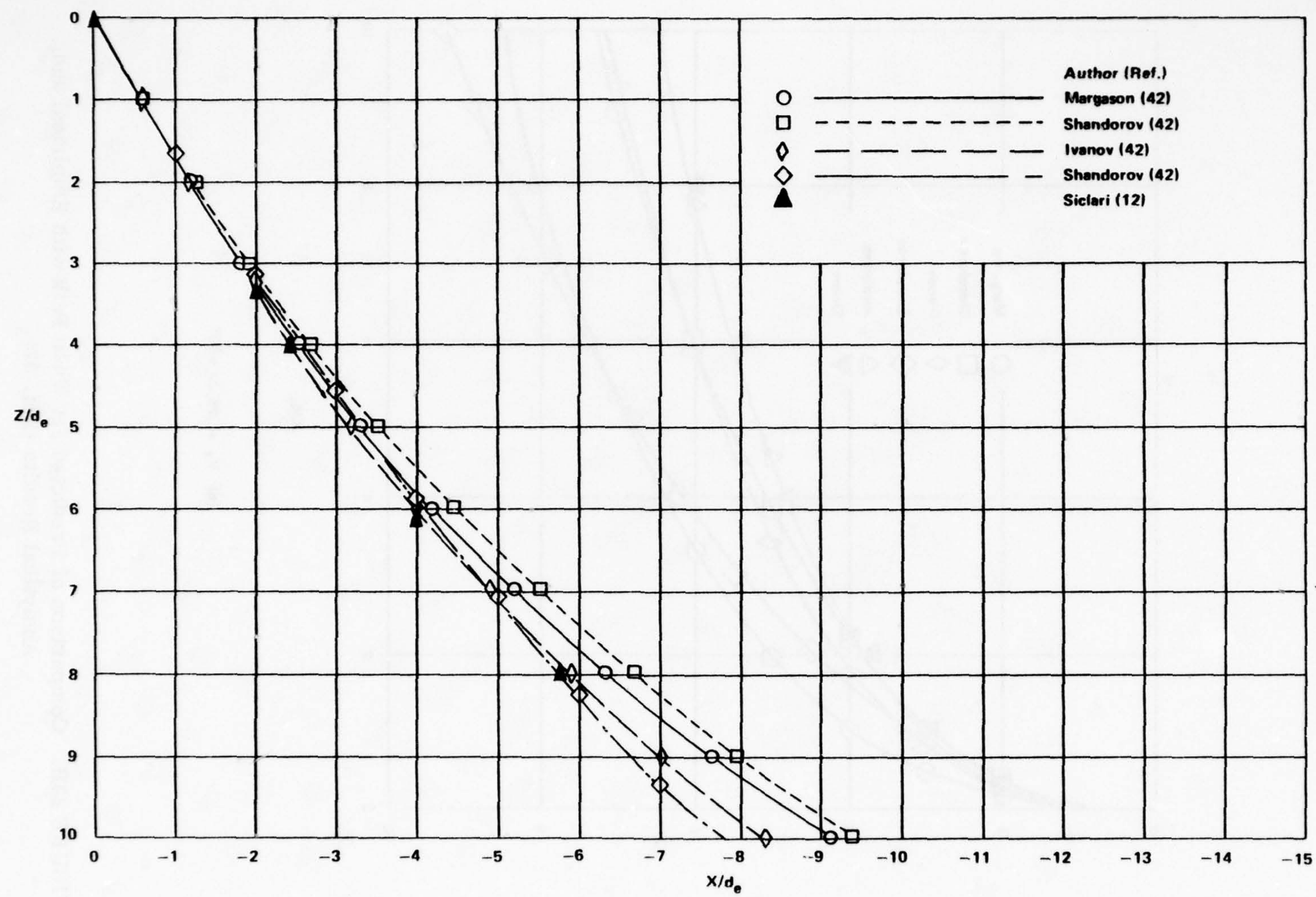


FIGURE 21. Induced Pressure Variation for a Spanwise Two-Jet Configuration (Spacing = $2.5\, d_e$, $\delta_j = 90°$, $U_\infty/U_j = 0.125$)



(a) Station $Y/d_e = 1.5$

FIGURE 22. Induced Pressure Variation for a Two-Jet Configuration at Sideslip $\beta = 20°$ (Spacing = $2.5d_e$, $\delta_j = 90°$, $U_\infty/U_j = 0.125$)



(a) $V_e = 0.100$, $\delta_j = 60°$

FIGURE 23A. Comparison of Predicted Jet Wake Path with Empirical and Analytical Results (Ref. 42)

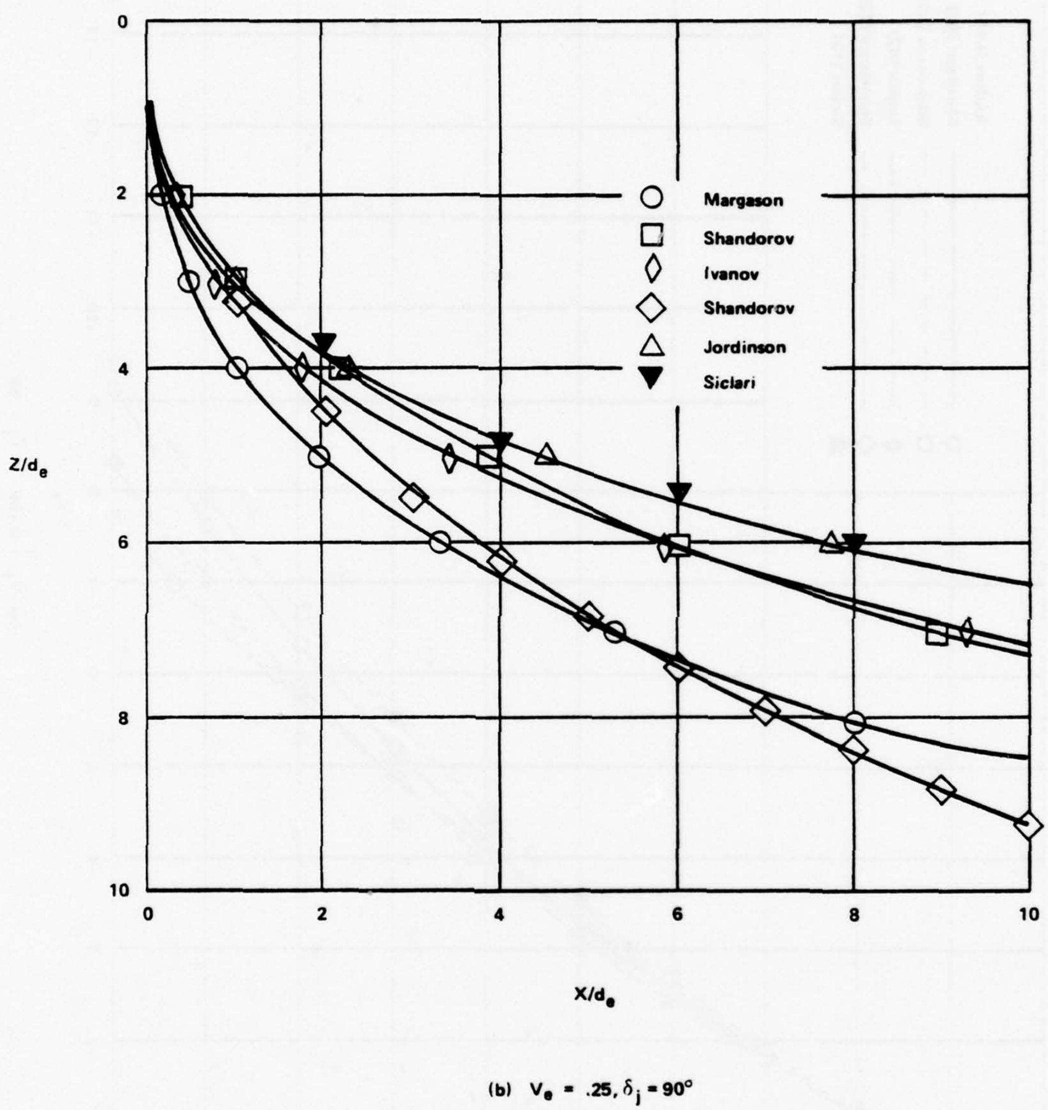
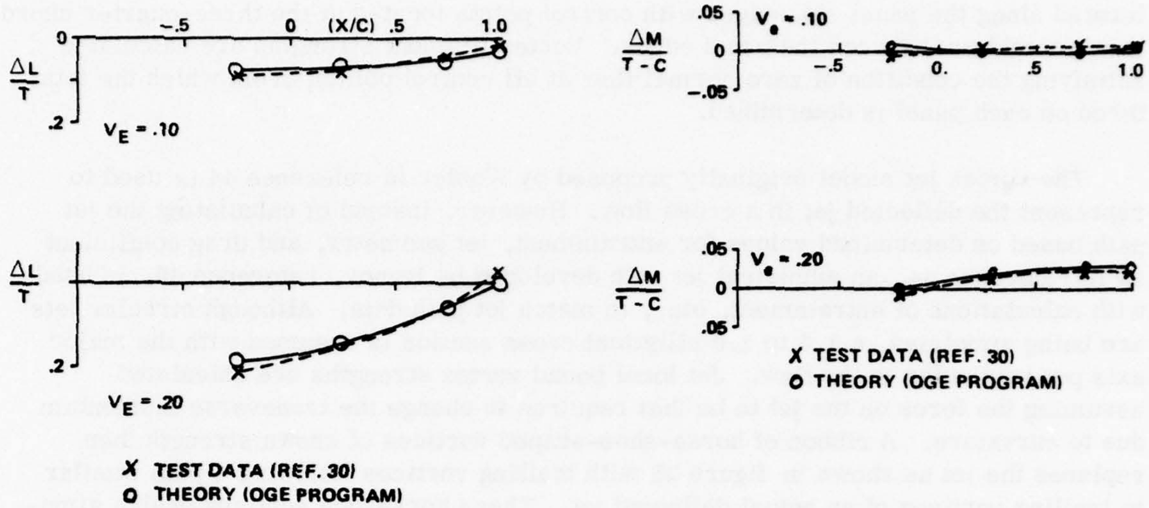
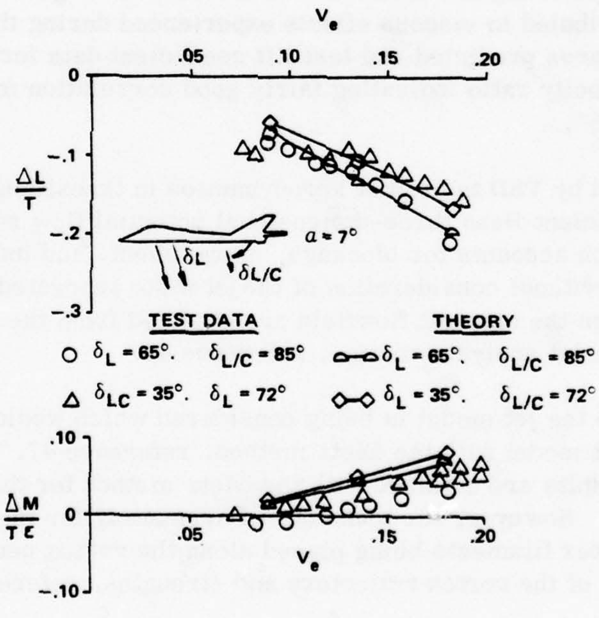


FIGURE 23B. Comparison of Predicted Jet Wake Path with Empirical and Analytical Results (Ref. 42)



(a) Variation of Jet-Induced Lift and Pitching Moment with Longitudinal Jet Location (Ref. 30)



(b) Predicted and Experimental Jet-Induced Characteristics with Supersonic V/STOL Aircraft

FIGURE 24. Correlation Between Theory and Model Test Data

located along the panel side edges with control points located at the three-quarter chord location midway between the panel edges. Vortex filament strengths are calculated satisfying the condition of zero normal flow at all control points, from which the total force on each panel is determined.

The vortex jet model originally proposed by Wooler in reference 44 is used to represent the deflected jet in a cross flow. However, instead of calculating the jet path based on determined values for entrainment, jet geometry, and drag coefficient as in reference 44, an empirical jet path developed by Ivanov, reference 45, is used with calculations of entrainment, etc., to match jet path data. Although circular jets are being simulated, a 1.5 to 1.0 elliptical cross section is assumed with the major axis perpendicular to the flow. Jet local bound vortex strengths are calculated assuming the force on the jet to be that required to change the transverse momentum due to curvature. A ribbon of horse-shoe-shaped vortices of known strength then replaces the jet as shown in figure 25 with trailing vortices following a path similar to trailing vortices of an actual deflected jet. These horseshoe vortices enable simulation of the jet effects on the external flow field.

An experimental program conducted to provide data for correlation with predictions from this technique obtained wing force and moment data. Good correlation between theory and test results for wing lift coefficient is indicated in figure 26 with variations in pitching moment attributed to viscous effects experienced during the wind tunnel tests. Figure 27 compares predicted and test lift coefficient data for varying angle of attack and effective velocity ratio indicating fairly good correlation for $\alpha = 0°$ but over-predicting C_L for $\alpha = 8°$.

A method employed by VSD to predict aerodynamics in transition and STO combines an improved, more efficient Hess three-dimensional potential flow routine with Wooler-Ziegler jet model, which accounts for blockage, entrainment, and indirectly, vortex generation, but again, without consideration of the jet wake separated region. The effects of engine inlet suction on the aircraft flowfield are obtained from the third part of the method, the Stockman inlet analysis routine, reference 46.

An improvement to the jet model is being considered which would replace the present Wooler-Ziegler jet model with the Dietz method, reference 47. Although obtained differently, similar results are obtained with the Dietz method for the jet entrainment and jet path centerline. However, the technique of accounting for the blockage effects is quite different with vortex filaments being placed along the vortex centerline based on detailed measurements of the vortex trajectory and strengths, reference 25.

Figure 28 shows reasonable correlation between results of this method and test data of ref. 37 for an aircraft/jet configuration that does not involve jet wake separation effects.

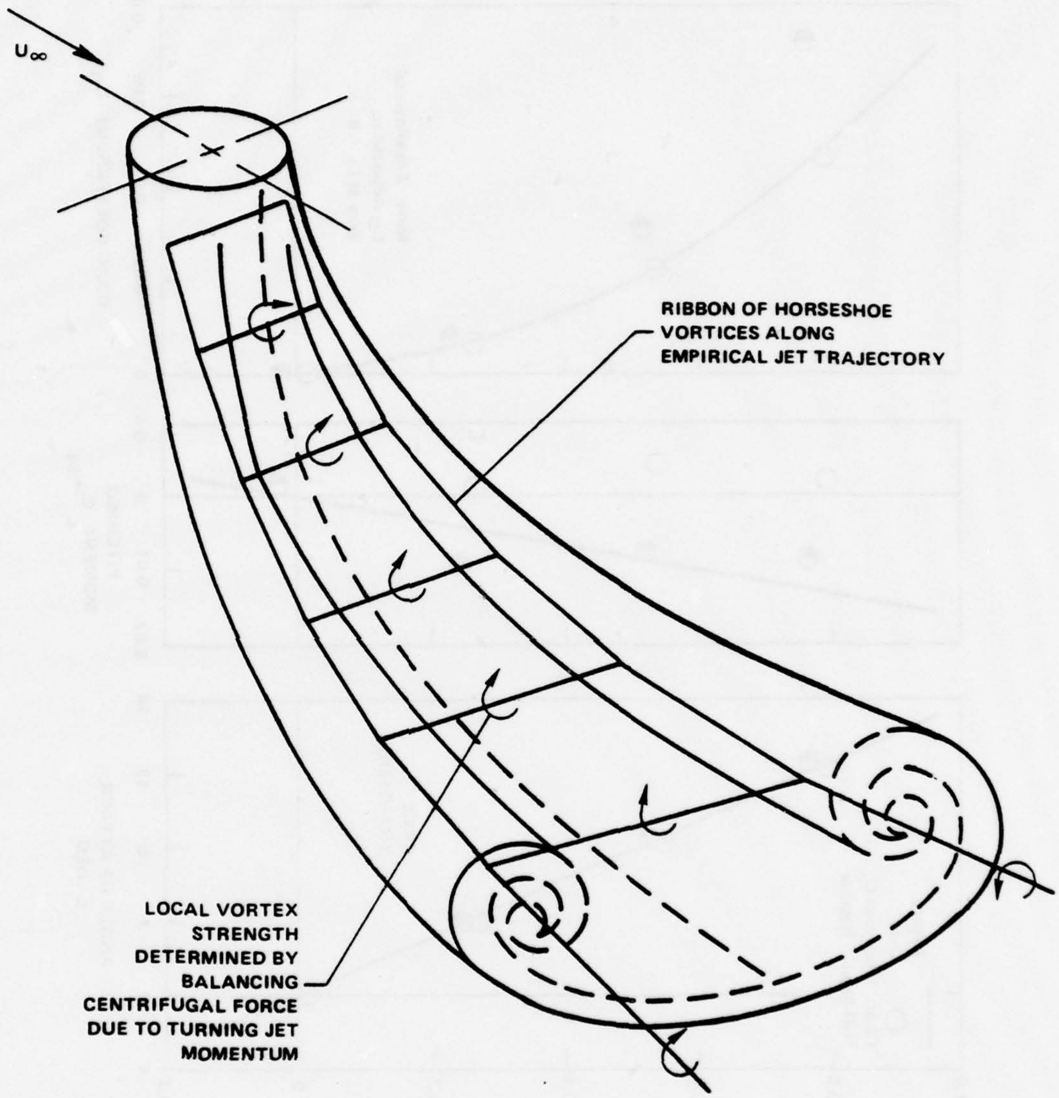


FIGURE 25. Ribbon Vortex Model of Jet-in-Crossflow

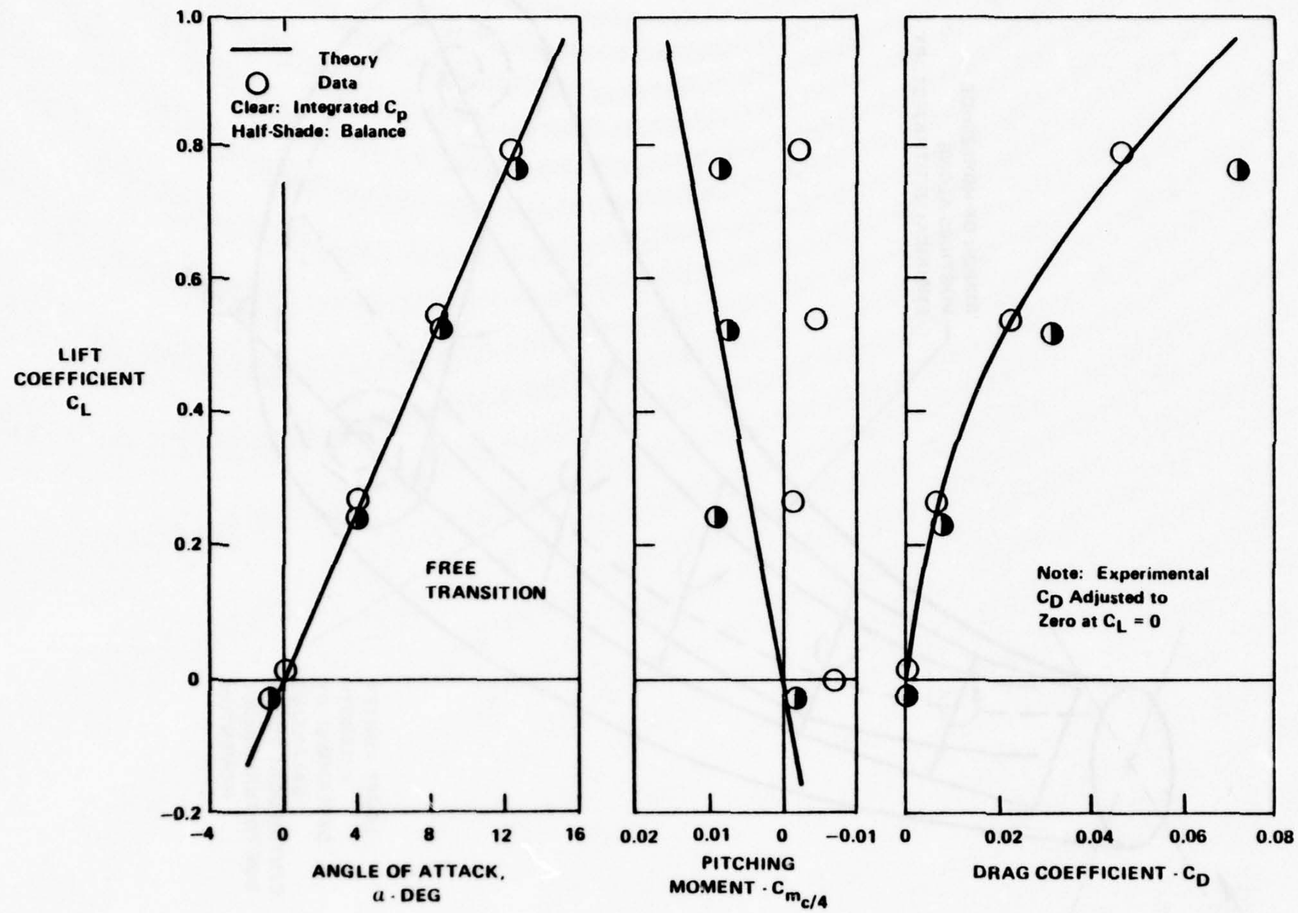


FIGURE 26. Correlation of Theoretical and Experimental Forces on the Wing Alone

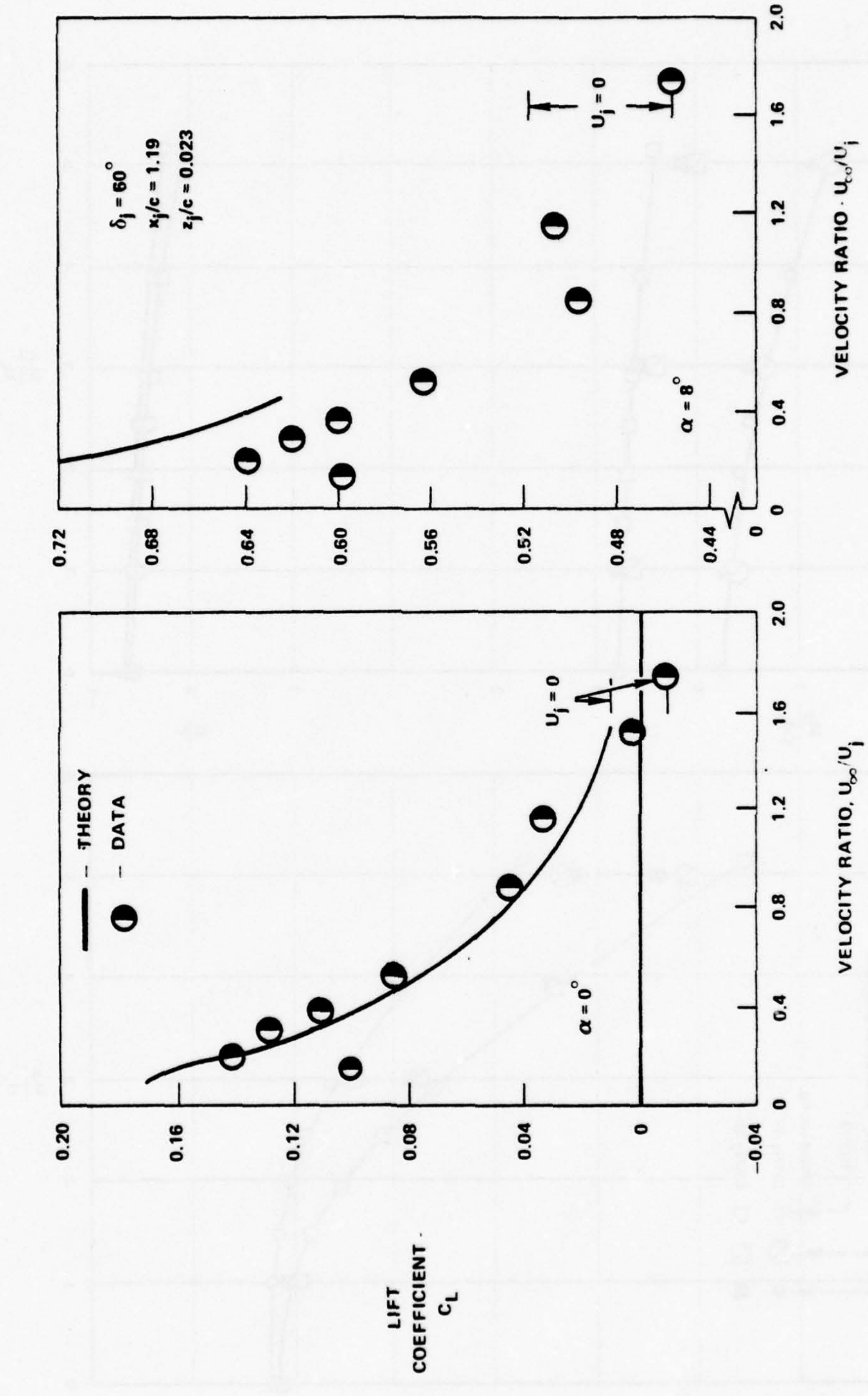


FIGURE 27. Variation of Lift Coefficient with Free Stream-to-Jet Velocity Ratio.

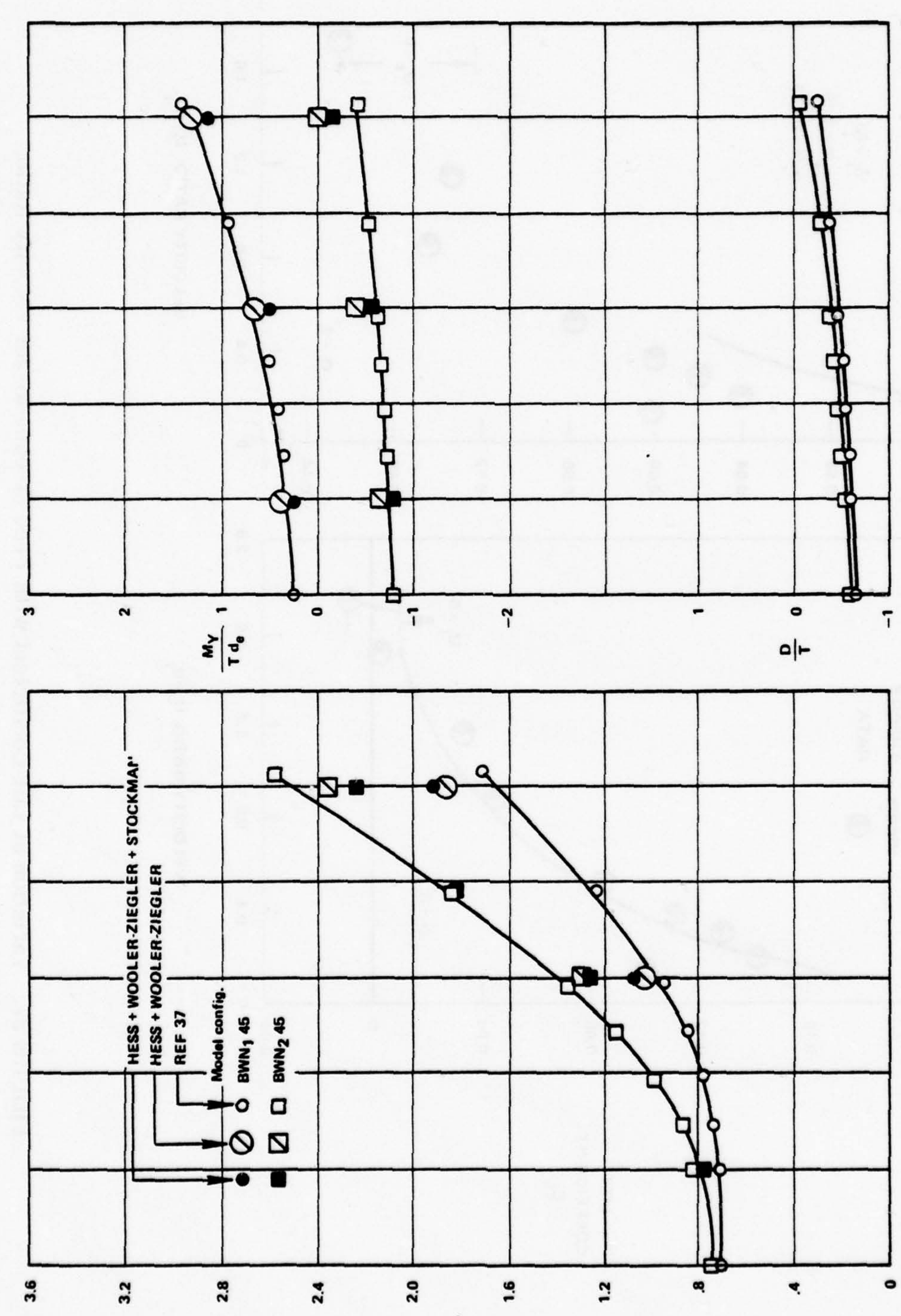


FIGURE 28. Effect of Thrust Configuration on Longitudinal Aerodynamic Characteristics at an Angle of Attack of 10° with Power.

A method developed by Rockwell for determining aerodynamic characteristics of augmentor wing concepts, reference 48, is based on a modification of the Maskell and Spence three-dimensional solution for determining the pressure distribution and lift on a jet flap wing, reference 49. Modifications consisted of replacing C_μ, the primary nozzle momentum coefficient in jet flap theory, with ϕC_μ, thereby accounting for the augmentation ratio, ϕ, associated with the augmentor wing. Corrections were also made to account for fuselage lift. Correlation of predicted data with test data of an augmentor wing model is shown in figure 29 for various momentum coefficients.

b. Summary of Transition Prediction Methods

In review, transition aerodynamics prediction capability of multi-jet V/STOL aircraft is typified by the technique developed at Vought which combines the Wooler-Ziegler jet model with the Hess aircraft paneling method. Blockage, entrainment and vortex generation of the jets are treated, but without consideration of wake effects. The Wooler prediction technique, reference 23, from which the Wooler-Ziegler jet model was taken, has similar application but uses a lifting surface, body transformation technique to model the aircraft and calculate the aerodynamic characteristics. A technique which also uses the Hess method was developed by Siclari, reference 12. However, the jet model developed for this technique does not account for the wake effects and the vortex generation, restricting its application to low speed transition. Another typical method of aircraft modeling uses the vortex lattice method as reported by Durando, reference 43, treating entrainment, vortex generation, and indirectly, blockage.

The evaluation of these techniques indicates the variety in approaches taken in their development, being dictated, understandably, by the requirements of individual V/STOL designs and interests. The very limited comparisons of prediction versus test data of these several methods shows variability in accuracy depending upon jet-to-surface location (as in Wooler correlations of reference 38) and on speed regime (as in Siclari's method). This indicates the need for an improved jet model to more accurately account for the four major viscous effects previously described and capable of analysis of jet induced effects regardless of jet location. A present program, sponsored by NADC to develop a computerized prediction technique for transition, includes consideration of the four viscous effects with analysis capability for arbitrary jet location. Numerous experimental investigations have been conducted to determine the variation in jet induced effects with jet exit geometry, number, inclination, location, and with effective velocity ratio. This body of data can readily be used as a basis for correlation with improved prediction techniques and also as a potential basis for pure empirical prediction formulations.

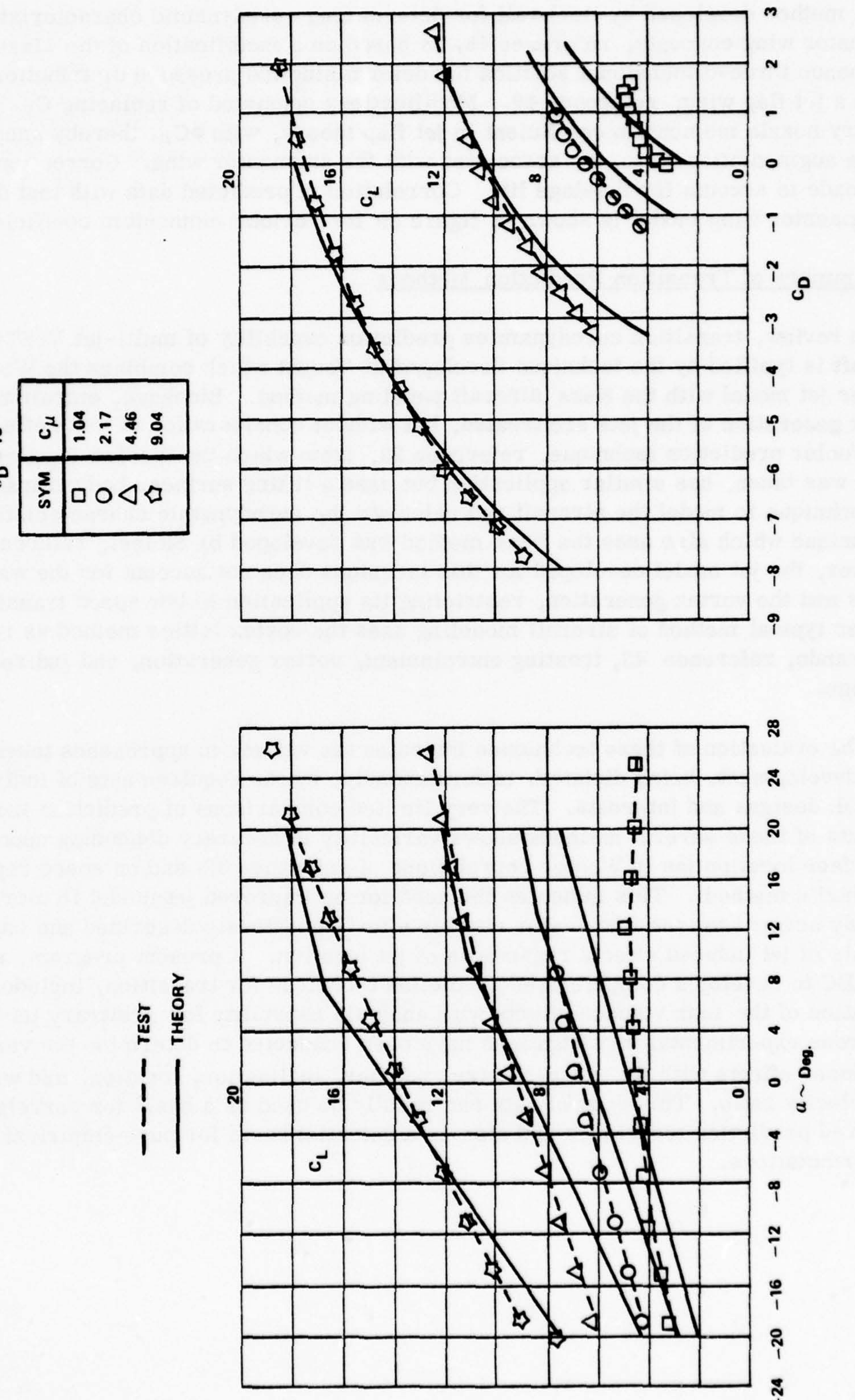


FIGURE 29. Comparison of Test with Modified Jet Flap Theory ($\delta_F = 54°$)

3. Propulsion Induced Aerodynamics in STO (IGE)

It is well known that a substantial increase in V/STOL aircraft payload or fuel lift-off capability is achieved when a rolling or short take-off is performed. Even for take-off runs of the order of 400 feet, afforded by small ship carriers, the STO can be accomplished with overload gross weights which in some cases double the VTO payload.

The critical flight area is the actual lift-off condition where adequate margins for stall and control usage must be preserved to allow for wind variables and attitude transients. Accurate knowledge of propulsion induced lift and moment effects in this flight condition are needed to insure reliable prediction of the true overload capability and control requirements.

Very little published test data and few prediction methods are available to indicate the magnitude of the induced forces and moments at STO flight conditions for jet or fan V/STOL's. As discussed by Flinn and Stalter, in reference 50: the flow field caused by jets issuing into the mainstream flow is complicated manyfold when the effects of ground proximity must be considered. At forward speeds in ground effect, the jet efflux is deflected aft before striking the ground. The upwash after impingement can occur at the tail surface and cause trim and stability changes.

If, however, the jets are positioned at high deflection angles ($\delta_j \approx 60°$) just prior to lift off, recirculation of the portion of the slipstream directed forward after impingement is a further flow field complexity that can occur.

It is useful to separate the problem into two distinct ground impingement situations; one in which the complete jet flow is deflected rearward after impingement, i.e., no recirculation of the jet; and the other in which significant recirculation occurs. The former condition is potentially amenable to solution by techniques which use an image system of the jet efflux below the ground, (such as the VSD modified Wooler-Ziegler). In the latter situation, extensive re-circulation may be beyond present flow modeling techniques and therefore is either to be extensively examined in model tests or deliberately avoided by operational flight procedures.

A defining boundary separating the two jet impingement flow situations described above has been empirically derived by two known test investigations; those of Tyler and Williamson, reference 51, and unpublished tests conducted by MAC.

In these investigations, ground flow tuft patterns were studied for conditions of a jet exhausting into a cross-wind at various angles to the free stream and impinging on a ground plane. Stagnation point locations were determined corresponding to both the jet impingement point and the point at which the wall jet is reversed by the free stream flow. From these data, conditions were determined at which the two points merge, thus identifying the limit beyond which forward wall jet flow does not occur, i.e. the jet is "blown back." Stagnation point positions and the conditions for disappearance of forward flow were found to correlate with the parameter $(U_\infty/U_j)(h/d_j)$.

Boundaries of incipient wall jet forward flow separations are presented in figure 30, as reproduced from the above reference work.

As was mentioned, very little published data or methods are available to indicate ground effects at STO conditions, particularly for the jet/fan class of V/STOL's. However, research efforts carried out in support of the AMST program (EBF, USB, and IBF concepts) give some insight into the nature of the ground effect problem, of the emerging analytical techniques to predict it, and some model and flight test data comparisons to indicate trends.

Representative of the evolving analytical methodologies which give some insight into the nature of the phenomenon is the recent work by Goldhammer, reference 52, being sponsored by NASA Ames. Key points from his work are as follows.

A detailed study of this problem indicates that three phenomena contribute to flow field changes as the ground is approached. Consider the ground to be simulated by placing an "image" airfoil at a distance 2h below the "real" airfoil. As shown schematically in figure 31, the image airfoil induces predominantly an upwash on the real airfoil for forward (unflapped) loading but predominantly downwash for aft (flapped) loading. Thus, this first effect would tend to increase lift in ground effect for a flat plate airfoil but would tend to decrease lift for a flapped airfoil, depending, of course, on the relative magnitude of the forward and aft loading. The second phenomena which contributes to ground effect is the perturbation velocity opposite to the free stream direction induced by the image airfoil. For positive lift, this effect of decreased dynamic pressure always reduces lift. The third effect is important only for large flap deflections. When a portion of the airfoil surface is highly deflected, downwash is no longer the predominant term in the boundary condition. Instead, the "u" perturbation velocity becomes of comparable magnitude. Since in ground proximity u induced by the image is generally opposite to the free stream, it follows that v must be smaller. For this condition to be satisfied lift must decrease.

The three phenomena discussed above cannot in reality be evaluated to assess the influence of ground proximity. The ultimate effect of ground proximity on lift is dependent on the relative importance of each phenomenon and can only be evaluated using a sophisticated analysis method which solves the complete ground effect problem. However, looking at the problem in this fundamental manner leads to understanding of the ground effect problem.

Typical effects on lift of ground proximity for jet-flapped airfoils computed by the method of reference 53 is shown in figure 32, and show a generally adverse effect of ground proximity. Note that the adverse lift effect generally increases with increased angle of attack and with increased blowing coefficient, C_μ.

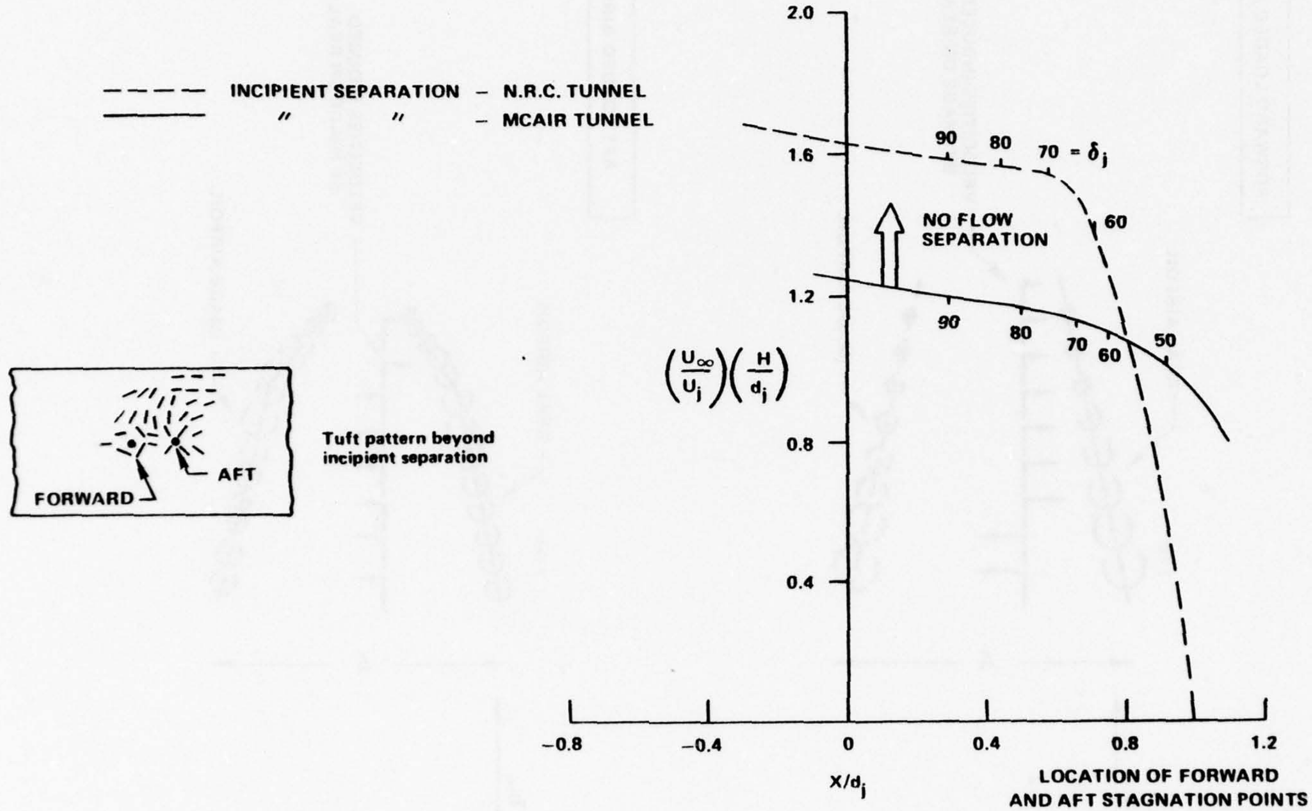


FIGURE 30. Boundaries of Jet Impingement Flow Pattern Change Comparison with Canadian N. R. C. Data

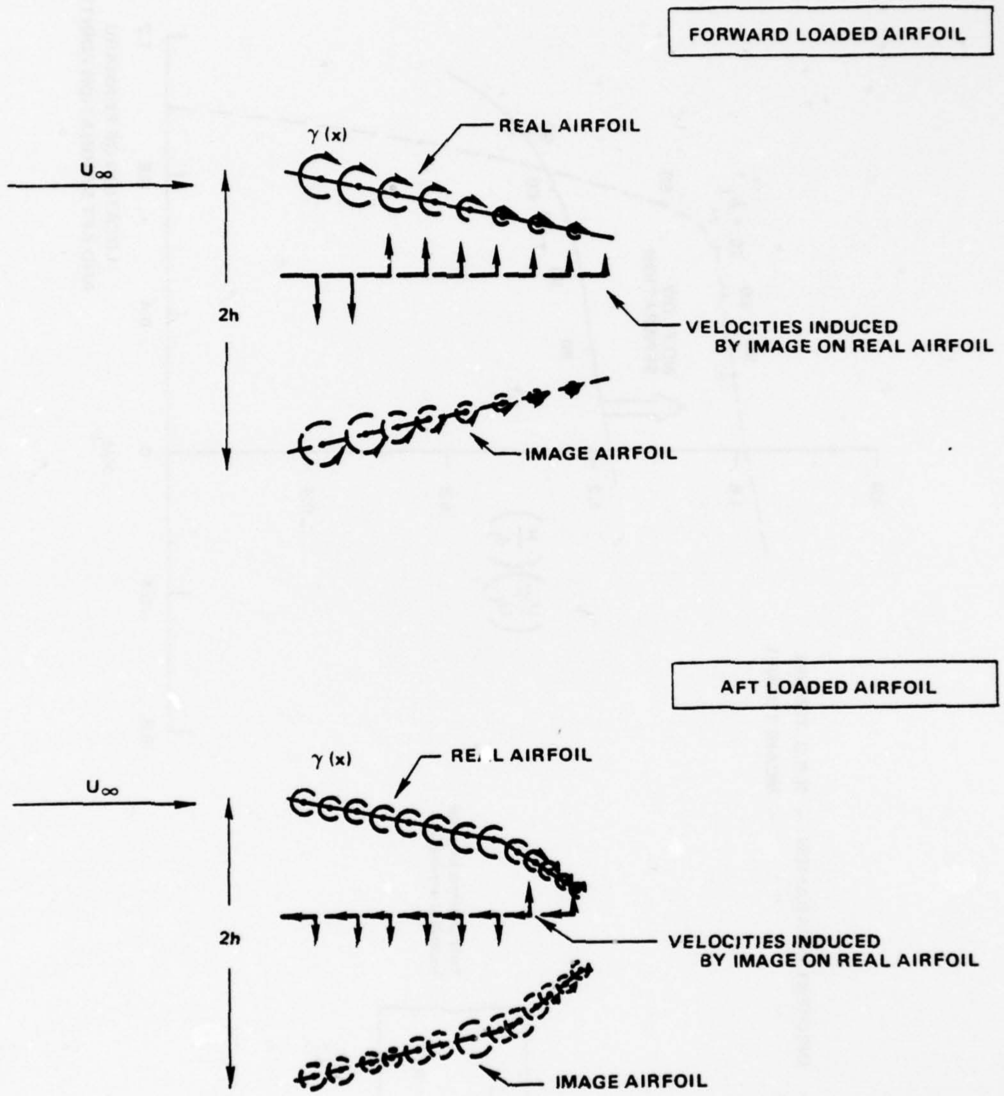


FIGURE 31. Schematic Illustration of Various Phenomena Contributing to Ground Effects

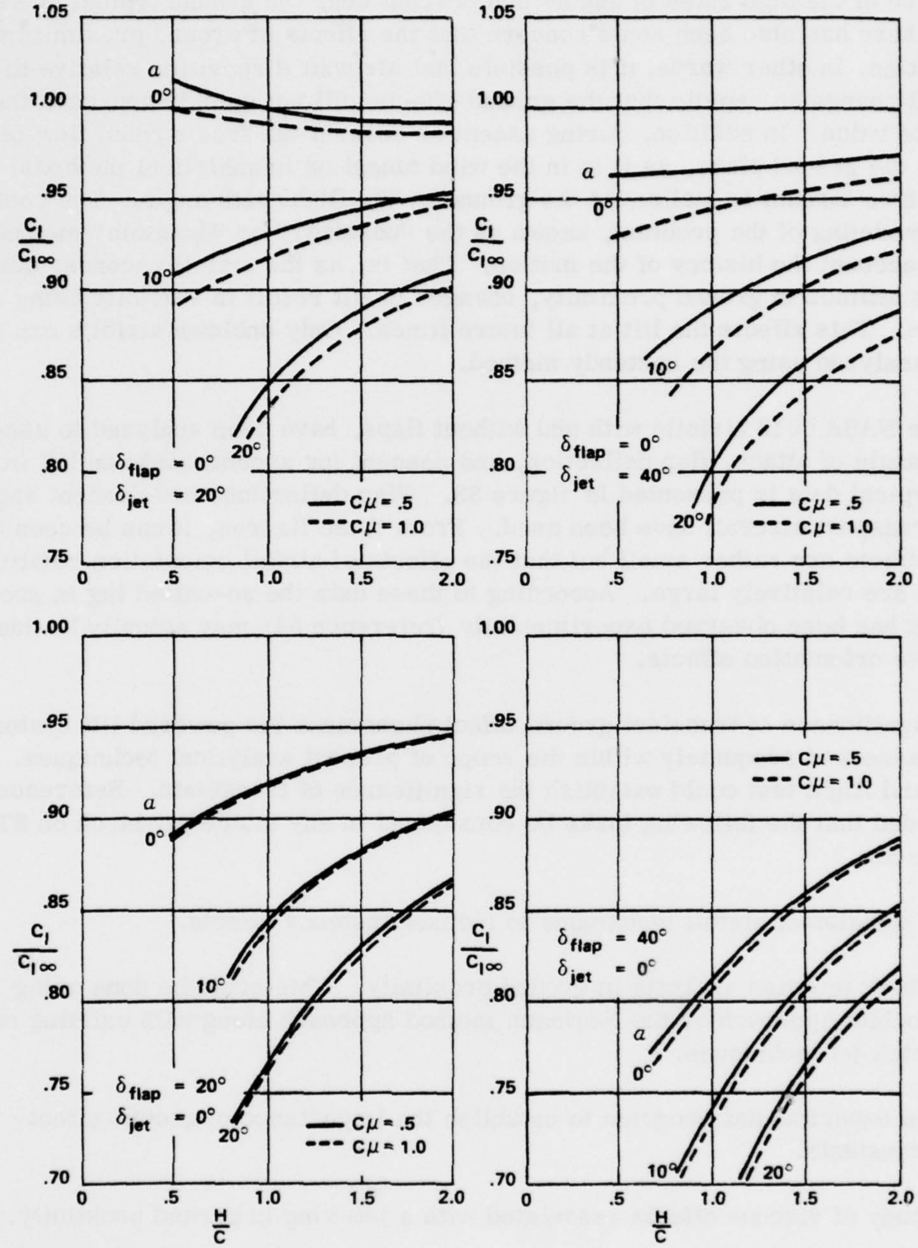


FIGURE 32. Ground Effect on a Two-Dimensional Jet-Flapped Airfoil Computed by the Method of Reference 52 ($c_f/c = 0.4$)

Because of the high rates of ascent and descent near the ground typical of STOL aircraft, there has also been some concern that the effects of ground proximity will lag the motion. In other words, it is possible that aircraft disposition relative to the ground will change so rapidly that the ground effects will not quickly approach their steady state value. In addition, during ascent or descent the free stream flow is not parallel to the ground plane, as it is in the wind tunnel or in analytical methods; but rather the free stream is inclined to the ground by the flight path angle. The complete transient modeling of the problem, known as the "unsteady" or "dynamic" method, takes into account the history of the motion. That is, as the airfoil ascends, descends, or changes attitude in ground proximity, changes in lift result in vorticity being shed in the wake. This affects the lift at all future times. Only unblown airfoils can presently be analyzed using the unsteady method.

Simple NASA 0012 airfoils with and without flaps, have been analyzed to assess the effects of angle of attack, flap deflection, and descent (or ascent) angle on lift in ground effect. Typical data is presented in figure 33. Flap deflections and descent angles of STOL transport aircraft have been used. From these figures, it can be seen that unsteady effects are rather small but that the effects of airfoil orientation relative to the ground are relatively large. According to these data the so-called lag in ground effects that has been observed experimentally (reference 54) may actually be due primarily to orientation effects.

The *significance of transient ground effect* phenomena for powered lift systems cannot be assessed adequately within the scope of present analytical techniques. Experiment and flight test could establish the significance of transients. Reference 52 recommended that the following tasks be considered in any future research on STOL ground effects:

Extension of airfoil techniques to include unsteady effects.

Thick jet/wind analysis in ground proximity. This could be done using a doublet approach or the Neumann method approach along with existing or new thick jet techniques.

An experimental program to establish the importance of ground effect transients.

Study of viscous effects associated with a jet-wing in ground proximity.

A recent summary of wind tunnel and flight test experience (C-8 augmentor, YC-14 and YC-15) on STOL ground effects is presented by J. P. Campbell in reference 55. This review of powered lift ground effect research was undertaken to explore the reasons for the apparent discrepancy between the pessimistic predictions of ground effect based on early wind tunnel research and the generally favorable ground effects exhibited by the three powered lift aircraft flown to date.

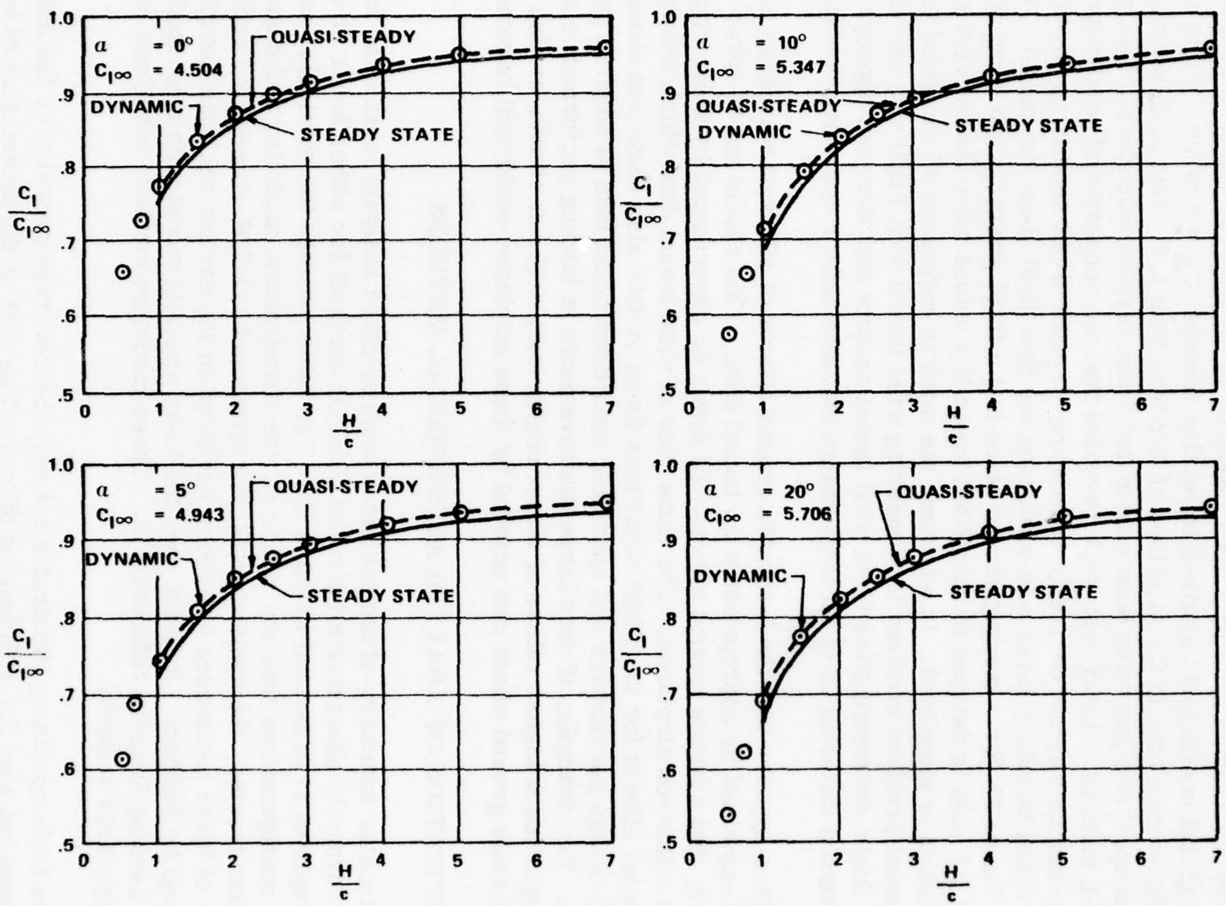


FIGURE 33. Comparison of Steady State, Quasi-Steady, and Dynamic Solutions for the Lift on a NACA 0012 Airfoil with Flap Descending Near the Ground ($c_f/c = 0.4$, $\delta_f = 60°$, $\gamma = 5.71°$ (10%)).

Early wind tunnel research drew attention to the adverse effect of ground proximity at the high lift coefficients attained in jet flap models (C_L = 6 to 10). Figure 34 illustrates the severe loss in C_L at values of H/c less than 1.5. Due to this concern, low wing transport designs were soon eliminated from serious consideration as powered lift STOL aircraft. Later test work revealed that the conventional wind-tunnel ground board technique was not correctly simulating airplane flight conditions because the ground board boundary layer was modifying the flow field about the model. Typical data in figure 35 for a moving ground plane and a fixed ground plane show that the adverse lift loss is delayed to somewhat lower H/c values when the correct ground plane motion is simulated. In addition, the work in reference 54 revealed that a fundamental problem involved in comparing wind tunnel with flight was one trying to predict flight characteristics from wind tunnel results that were not appropriate due to substantial differences in aircraft design features and/or operating conditions.

It thus appears that the favorable ground effects of all three airplanes can be readily explained by appropriate wind tunnel data. This should not be taken to mean, however, that adverse ground effects will never be experienced by these airplanes or similar follow-on airplanes. The same sets of wind tunnel data which indicate positive ground effects for the flight conditions flown to date also show that changes in aircraft design parameters and operating conditions could lead to adverse ground effects. For example, if very large improvements in landing performance are sought by going to much higher values of thrust coefficient, angle of attack, or flap deflection, the favorable ground effect now enjoyed by these airplanes could well become adverse.

CLASSIFICATION OF ANALYTICAL/EMPIRICAL METHODS

A tabular summary of the published computerized analysis techniques for predicting aerodynamic characteristics of jet V/STOL aircraft for either hover or transition flight regimes is presented in table III. The table outlines the particular aerodynamic and jet configurations that are analyzed, the aerodynamic modeling technique used, the jet effects treated, the applicable flight regime and V/STOL concept for each technique. Details of these techniques have been reviewed in the earlier sections except for that developed by Rubbert. Rubbert uses the Hess paneling model with a jet model similar to that used by Siclari, reference 12. These modeling methods have been discussed in the previous sections.

The table concisely illustrates not only the coverage provided by the individual techniques but also the deficiencies discussed as part of the summaries of hover and transition. The lack of treatment of the separated wake region along with the varied coverage of the other jet effects by the individual techniques is clearly shown. Additionally, a lack of analysis techniques is also evident for determining the aerodynamics of transition in-ground-effect (STO) of jet V/STOL aircraft, and also for addressing the thrust augmented wing concept.

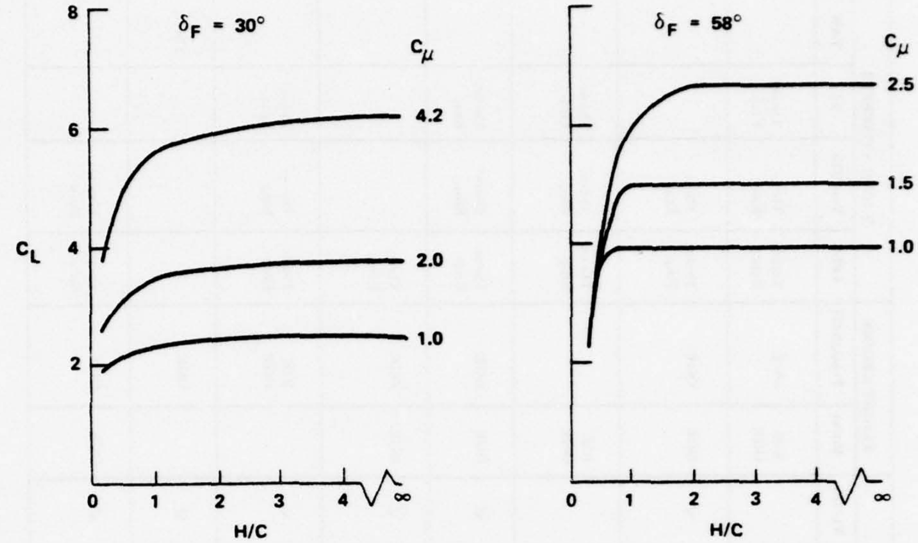


FIGURE 34. Early Two-Dimensional Jet Flap Data
$\alpha = 0°$

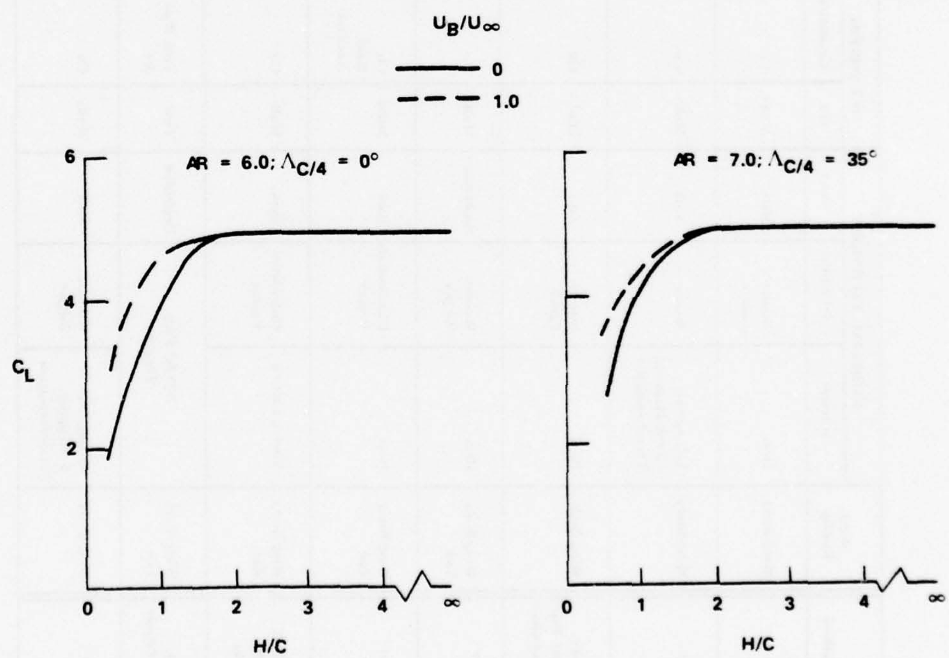


FIGURE 35. Effect of Moving Belt Ground Plane. Jet Flap, $\delta_f = 60°$, $\alpha = 0°$

TABLE III. CLASSIFICATION OF COMPUTERIZED V/STOL AERODYNAMIC PREDICTION TECHNIQUES

Method	Aero Config.	MODELING TECHNIQUE			JET CONFIG.		JET MODEL EFFECTS				FLIGHT REGIME		V/STOL CONCEPTS			
		Aircraft	Jet Efflux	Inlet	No.	Geometry	Blkge.	Entrmt.	Wake Sep.	Vortex	Hover	Trans/STO	LPLC	Vec. Thr.	TC	TAW
Migdal Siclari	Wing-Body	Hess	Source Panels	Sink	Multi	Cir	√	√			IGE OGE	OGE	Theor/ Emp	Theor/ Emp	Theor/ Emp	
Wooler	Wing-Body	Lifting Surface & Mapping Transformation	Wooler	Sink	Multi	Cir	√	√		√	OGE	OGE	Theor/ Emp	Theor/ Emp		
Kotansky, Durando, Bristow, Saunders	Wing-Body	Hess	Source Panels	Sink	Multi	Cir	√	√			IGE OGE		Theor/ Emp	Theor/ Emp	Theor/ Emp	
Vought	Wing-Body Tail	Hess	Wooler/ Ziegler	Stockman	Multi	Cir	√	√		√	OGE	OGE	Theor/ Emp	Theor/ Emp	Theor/ Emp	
Rubbert	Wing-Body Tail	Hess	Distributed Vortex	Sink	Multi	Cir, Rect, Annular		√		√	OGE	OGE	Theor/ Emp			
Rozendaal, Schmidt, Durando	Wing-Body Tail	Vortex Lattice	Distributed Vortex	Sink	Multi	Cir		√		√		IGE OGE	Theor/ Emp	Theor/ Emp	Theor/ Emp	
Stewart, White, Palmer	Wing-Body Tail	3-D Jet Flap Theory		Neglected	Two	Thin Wall Jet	√			√		OGE				Theor.
Wooler, Ziegler	Wing-Body	Lifting Surface & Mapping Transformation	Wooler/ Ziegler	Sink	Multi	Cir	√	√		√	OGE	OGE	Theor/ Emp	Theor/ Emp		

This lack of generalized methods for addressing the thrust augmented wing concept is understandable due to its less widespread interest among investigators. Such is not the case for the other deficiencies. The separated wake region has long been recognized as a major source of error in a number of techniques and as a difficult analysis problem, but with very little effort expended to solve it. However, a number of methods have recently been proposed to attack this problem and a recently initiated program sponsored by NADC to develop a computerized prediction technique for transition will include analysis of these wake effects.

With the attractive payoffs in payload or range to be achieved with short take-off, and in light of the discussion in the previous section and the present investigation sponsored by NADC, improved techniques applicable to transition, or STO, will be forthcoming.

SURVEY OF INDUSTRY APPLIED METHODS AND RESEARCH RECOMMENDATIONS

Briefings and discussions were held with a number of aircraft companies and research agencies involved in V/STOL developments to obtain further information regarding the state-of-the-art of V/STOL aerodynamics, and to elicit technology problem areas suggested for future research.

The companies and agencies contacted to date are:

- Boeing Company
- Grumman Aircraft
- McDonnell Aircraft
- NASA, Ames
- NASA, Langley
- Northrop Aircraft
- Rockwell, Columbus
- Vought Aeronautics

Future visits are planned as part of the continuing efforts in V/STOL aerodynamics and stability and control technology developments.

HOVER JET INDUCED AERODYNAMICS

A variety of methodologies and practices with regard to determination of jet induced effects in the hover mode were obtained ranging from essentially complete reliance on testing to the quite complex computerized methodologies employing aircraft paneling plus jet and fountain empirically based models.

One observation made from the first approach (extensive testing) is that a sizeable variation of induced effects can result from small changes in vehicle undersurface design, e.g., door arrangements or strake locations, which cannot be readily predicted by analytical methods. A suggested approach is to employ the best available gross prediction technique - either fully empirical or analytical/empirical - in the early conceptual design phase to rule out undesirable jet arrangements and work towards the better compromises, then resort to model testing to determine the desired finer tuning of jet spacing, canting - and aircraft under surface shaping.

In the early parametric design phase, thrust loss penalties due to jet induced suckdown and inlet reingestion are usually assigned values based on gross estimates obtained from composite experimental results such as that of Margason and Vogler or in-house developed empirical methodologies such as reference 18. Quick methods are indispensable when developing preliminary design concept comparisons for an array of point design options. However, as shown in the design sensitivity studies of reference 56, V/STOL design gross weight is highly sensitive to vehicle rated thrust to weight, T/W, indicating the importance of reasonable accuracy in thrust loss estimates.

The V/STOL in ground effect problem is greatly accentuated when large roll or pitch attitudes relative to the ground plane are to be considered. For small ship carriers in high sea states, ship deck attitudes can exceed 10 degrees, and when coupled with aircraft attitude changes due to wind turbulence, further thrust penalties due to suckdown and control usage must be assigned.

It has been determined experimentally that roll attitude instability always occurs in ground effect, i.e., the low wing experiences increased suckdown and the fountain, when present, shifts to the high wing side. A similar mechanism occurs with pitch attitude change, but due to the lack of fore and aft symmetry it is not necessarily predisposed to a pitch attitude instability. Limited test experience with a dynamic ground plane indicates that a significant amplification of these unstable moments can occur. There is at present a lack of published data to account for these attitude effects. However, an experimental test program is being initiated by NADC in FY77 to develop such data for both the static and dynamic deck motion conditions.

It was generally felt that with the existing and forthcoming data base on static hover ground effects, a reasonably good empirical DATCOM type methodology could be developed to determine major jet induced effects. The essential approach is to separate the induced suckdown effects from the pure fountain effects. The fountain is the most difficult effect to evaluate, especially with regard to non-normal jet impingements and unequal jet thrust conditions. It was suggested that a full assessment of the available test data might be in order to determine gaps or deficiencies in test data required for empirical formulations and for correlation with analytical prediction techniques.

A suggested effort as an alternative to the development of V/STOL design charts (e.g. DATCOM) for prediction of hover or transition V/STOL aerodynamics would be the use of a simple model of the aircraft, such as a flat planform, in lieu of the complex, three dimensional, fully contoured aircraft model for use in the potential flow analysis computer program.

TRANSITION AERODYNAMICS

The most widely used computerized methodologies for predictions of multi-jet/fan V/STOL aircraft aerodynamics in the transition flight mode employ potential flow solutions, with boundary conditions of no normal flow at aircraft surfaces and with empirically derived jet induction effects. Aircraft surfaces are modeled by either source panels or distributed vortex singularities.

The aircraft surface modeling techniques are of the Hess or vortex lattice techniques discussed in the section concerning computerized techniques. Evolving techniques are seeking optimum combination of source and doublet distributions to improve estimates in regions of complex geometry such as wing leading and trailing edges.

The Hess paneling technique is used almost exclusively for hover predictions where the ratio of induced velocity to free stream velocity is high. In the transition flight mode, the Hess or vortex lattice techniques have generally equal application, with the former giving somewhat increased accuracy but at the expense of increased modeling input time and computer usage time. The choice comes down to accuracy versus computational efficiencies together with theoretical limitations (i.e., small perturbation assumptions). Generally satisfactory prediction capability is afforded by the surface modeling techniques. The major area of concern is the input time with efforts presently being devoted to automated input routines.

Jet models for transition flight are usually of the Wooler form involving either a pure vortex distribution or a source and doublet distribution. A major deficiency in all of the jet models as previously discussed is the inaccurate accounting for the jet wake separated region. Wooler has suggested an empirical add-on effect for the wake region as described in reference 23, for cases in which significant surface area exists behind the jet. A recently initiated effort at VSD will address this deficiency by locally adjusting the entrainment or vortex effects.

The computerized methods for transition are generally employed in the preliminary design stage when the overall configuration concept has been selected. Overall aerodynamic force and moment coefficients and slopes are estimated for the wing/body/nacelle combination. Local downwash characteristics at the tailplane are also computed to evaluate the location and sizing of the horizontal tail and elevator for static stability and control. In addition, local surface loadings and pressure distributions are obtained for air loads analysis.

Somewhat simpler but faster aerodynamic analysis techniques for multi-jet/fan V/STOL's are applied at the conceptual design stage using the component build-up approach for conventional aerodynamics afforded by DATCOM, and add power effects incrementally, i.e., inlet ram drag and moment arm, Δ L/T, etc. estimated from applicable test data.

For the augmentor wing V/STOL's, apparently satisfactory predictions have been made by application of the three dimensional Maskell and Spence jet flap theory in which the primary nozzle isentropic jet momentum coefficient, C_μ, is replaced by ϕC_μ, ϕ being the ejector augmentation ratio.

A brief overview of the various computerized aerodynamic methodologies employed by the different aircraft companies are presented in table III.

Overall, significant problems noted in most of the applied computerized methodologies are:

1) Inefficient methods for data input of aircraft source panels or vortex lattice distributions - this becomes especially time consuming when effects of sideslip are required.

2) No account of interaction of both the aircraft induced flow field and the ground induced flow field with the jet flow conditions - in close ground proximity.

3) Inadequate accounting of the jet wake separation region.

4) Recent findings of Kuhlman from tests of jets in a crossflow having skewed exit profiles indicate significant reductions in jet induced suckdown with increased skewness. This skewness effect is accounted for in the Wooler/Ziegler jet model, but needs verification using Kuhlman's data.

SUMMARY OF RESEARCH RECOMMENDATIONS

A number of problem areas in V/STOL aerodynamic technology were identified by industry sources as requiring future research investigations. The list of these recommended investigations that follow are presented in a descending order of priority roughly based upon the number of independent sources making the recommendation.

1. Investigations to determine the proper jet efflux "characterization" to relate model data to full scale.

Jet spreading rates are highly coupled with ground induced forces and moments. For instance, jet spreading is closely coupled with entrainment which is responsible

for suckdown. It is obviously desirable to be able to develop full scale aircraft reliably from model testing. Previous work has demonstrated a highly non-linear dependence of jet spreading rates on jet physical size within augmenters. It is not known at present if this dependence continues with external flows, although reported tests on the AV-8B indicate significant disparities between model and full scale wind tunnel tests in ground effect.

A program envisioned would use several geometrically scaled disparate sized pairs of jets impacting on a ground plane. Operating conditions would be at relatively low mach numbers (to avoid compressibility interference) but identical Reynolds numbers; the low mach number requirement would be compatible for both lift fan and augmenter designs. By measuring the jet parameters at the nozzle and the jet decay and spreading rates of the jets prior to impact of the resultant wall jets, and of the ensuing fountain jet, scale dependence would be found in terms of eddy viscosities and/or power spectral density and RMS jet turbulence intensities.

2. Development of generalized hover suckdown/fountain design charts by correlations of available test data, supported by existing prediction methodologies (Wyatt, Siclari, Karemaa, etc.)

The background and approach have been discussed in sections concerning hover.

3. Development of improved V/STOL aerodynamic prediction techniques for short takeoff (STO) flight conditions (IGE).

The background for this problem area is discussed in the section concerning propulsion induced aerodynamics in STO.

4. Model test investigation of the coupling between ground induced forces/moments and aerodynamic forces/moments over a range of aircraft attitudes and ambient wind directions and velocities.

The coupling could be determined by comparison of forces/moments for: (a) wind on, lift devices off; (b) lift devices on, airframe aerodynamically shielded; and (c) wind on, lift devices on.

5. Analytical and experimental investigations of rectangular jet flow fields and induced aerodynamics.

First efforts on this problem area are being undertaken on a test and analysis program for jets of AR = 4 being conducted by LTV and sponsored by NASA Langley and NADC, and in a recently initiated test program by McDonnell-Douglas for jets of AR = 4 to 8, sponsored by NASA Ames.

6. Development of improved analytical techniques to describe wake effects behind jets in crossflow.

The background of this problem area is discussed in Section 2.

7. Determination of the thrust recovery of jets.

Experimental data have shown a reduction in apparent drag at forward speed when direct thrust effects are subtracted from the overall power-on data. This program would be experimental in nature using initially a 2-D wing with circular jets exhausted at various angles to the wing (piped air). Lift and drag will be recorded along with thrust, and far field pressure surveys made to define jet shape, inclination, and momentum flux.

8. Extension of present hover prediction methodology to time dependent flow fields involving heaving/pitching decks and unsteady crosswinds.

As mentioned, this problem area is already being addressed in a recently initiated contractual program by NADC.

9. Verification of present aerodynamic prediction methodologies with wind tunnel experiments of complete multi-jet models.

This task is included in a development program for an improved aerodynamic prediction methodology for transition/STO, recently initiated by NADC.

CONCLUSIONS

An assessment of available methods to predict the aerodynamics of V/STOL aircraft has been made by evaluating the various prediction methodologies in the literature and by reviewing the data base of past and on-going experimental programs. This assessment covered the hover and transition flight regimes in- and out-of-ground effect for the jet/fan lift and augmented wing V/STOL concepts.

Representative methodologies were evaluated with regard to method basis, capabilities and limitations, and accuracy assessment through available correlations with test data. The analytical methods typically combine an empirically-based jet model (the Wooler jet being widely used) with a potential flow analysis using a panelling technique (such as the Hess panel routine) or vortex lattice for modeling the aircraft. The Hess panel technique or vortex lattice technique generally have equal application in transition with the former giving somewhat increased accuracy but at the expense of increased modeling input time and computer usage time.

For the hover mode, a reasonably good data base and empirical formulations exist for predicting the lift loss due to entrainment effects both IGE and OGE of axisymmetric jet configurations. However, a major deficiency exists both in available data base and prediction methods relative to fountain induced effects. Attempts are presently underway to alleviate this deficiency with testing programs at Grumman, GD/Fort Worth, and MAC designed to increase the basic understanding of fountain flow properties and resulting interference effects.

Methodologies used for the prediction of transition aerodynamics generally provide adequate accounting of the flow blockage, entrainment, and vortex generation effects, but a limitation in all methods is the absence of jet wake separation considerations. This deficiency is being addressed as part of a present program at VSD to develop a comprehensive transition prediction methodology, investigating two approaches towards the development of an accurate wake separation prediction technique.

The prediction techniques for transition aerodynamics in ground effect (STOL) use image methods that are limited to no jet impingement. The data base largely pertains to blown flap STOL transport configurations. Test data generally show positive effects down to close ground heights ($h/\bar{c} \approx 11.0$) below which a sizeable lift loss occurs. The VSD program referred to above will also provide a technique for calculation of STO aerodynamics.

A basic lack of test data and prediction methods exist for analysis of V/STOL configurations employing non-circular jets. However, two experimental programs presently underway are investigating rectangular jets in hover ($A\!\!R$ = 2-8) and transition ($A\!\!R$ = 4) from which analytical jet models will be developed.

A common characteristic of the computerized analytical methods is the cumbersome input requirements and excessive computing time. As a result, these methods generally are employed in preliminary design only when the overall configuration has been selected. Various sources are attempting to automate the input routine and improve calculation efficiency to reduce usage time.

RECOMMENDATIONS

Further investigations in the areas outlined below are desirable to advance the understanding of V/STOL aerodynamics and the capability of prediction methodologies.

1. Further basic methodical tests of hover fountain effects and the development of generalized hover suckdown/fountain design charts by correlation with available data.

2. Investigations of effects of jet flow turbulence intensities and profiles, and the characterization required to relate model data to full scale.

3. Development of a methodical data base on jet/fan V/STOL for the STOL flight mode.

4. Continued efforts to improve the efficiency of data input packages and computational routines of computerized analytical techniques.

5. Continued assessment of V/STOL aerodynamics with emphasis on the physical and mathematical bases of the current V/STOL aerodynamic theories.

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